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INTERNAL FAULTS IN OIL-FILLED DISTRIBUTION TRANSFORMERS

FAULT MECHANISMS AND CHOICE OF PROTECTION

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INTERNAL FAULTS IN OIL-FILLED DISTRIBUTION TRANSFORMERS

FAULT MECHANISMS AND CHOICE OF PROTECTION

by

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PREFACE

This thesis is a report on the research work done for the degree of "Doktor ingeniør" at The Norwegian Institute of Technology (NTH) during the years 1989-1993.

The experiments were carried out during the years 1990-1992 as a part of a research project at the Norwegian Electric Power Research Institute (EFI), and was sponsored by the Federation of Norwegian Utilities (NORENERGI).

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SUMMARY

The aim of this work has been to study internal faults in mineral-oil-filled distribution transformers. In this work, main emphasis is placed on experimental work, both on full scale and model transformers. The service experience and fault statistics of distribution transformers situated in cable networks show that the failure rate of these transformers is less than one fault per thousand transformer years. Because of the low failure rate, the main argument for the overcurrent and fault-current protection of distribution transformers situated in cable networks is to ensure the safety of the general public and operating personnel by protecting against explosions or violent transformer tank rupture.

In the literature there is general agreement that the great majority of internal faults in distribution transformers starts as insulation faults and short circuits between neighbouring turns or layers in the medium voltage (MV) winding. The insulation failures can be triggered by factors such as thermal failures, mechanical stresses, electrical failures or ageing processes. Similar failures may also occur in the LV winding.

Internal short circuits were established between turns in the winding of a single phase transformer model. Preliminary studies focused on the development of the fault. By help of measurements and calculations on this model the average temperature in the short-circuited turns was found to be about 600-700 °C at the time when the fault developed further.

Literature searches and laboratory tests have shown that a variety of gases can be produced by a fault in the windings in an oil-filled distribution transformer. Methane (CH_4), ethylene (C_2H_4) and propylene (C_3H_6) are produced in large amounts in the case of local heating. Hydrogen (H_2) and acetylene (C_2H_2) are produced in large amounts by arc discharges in oil. If solid insulation materials are affected, large amounts of carbon monoxide (CO) and carbon dioxide (CO_2) will also be generated. Oil vapour and oil mist will also be created when the oil is heated. The explosion limits (in % by volume in air) for some of the gases and the oil mist are wide, and the self-ignition temperatures are relatively low.

Full scale tests with internal short circuits between neighbouring turns and layers of turns in three phase distribution transformers have been carried out. These types of faults developed in different directions. The fault may develop further and involve other turns, or the short-circuited turn may melt off. Contact may be established between other turns, and the transformer appears to work normally again. The fault may also redevelop later. In three of the five tests, the fault development was progressive, and more and more turns were included in the short circuit.

With only one turn short-circuited, the increase in the initial line current is relatively small. The tests showed that the line currents may quickly reach values of several times the rated primary current of the transformer at the time when the fault develops further. Gas bubbles were seen to evolve from the region of the faulty winding. Large amounts of gas were produced in some of the tests.

Star-connected transformers with unearthed neutral allow the primary neutral point to float with respect to ground. This reduces the voltage across the faulty winding when the number of short-

circuited turns is increasing. Because of this, the increase in primary line currents will be larger for a delta-connected transformer than for a star-connected transformer when the short-circuited part of the winding is increasing.

A recently occurring internal fault in an oil-filled distribution transformer[1] has shown that violent accidents caused by explosion of generated gases and oil mist may occur even if the line currents do not reach large values. A similar occurrence is also known of, but with the fault in the low voltage (LV) winding[2].

Tests with internal power arcs between two neighbouring MV phases in oil-filled distribution transformers have also been carried out. The gas evolution and pressure rise in the transformers in some of the tests was considerable. The tests showed that if momentary development of internal power arcs in distribution transformers occurs, it is very important to reduce the arcing time and the arcing energy to a minimum in order to avoid violent cracking or explosion of the transformer tank. Current limiting MV fuses are very effective as protection against this seldom or almost never occurring fault.

Tests with internal short circuits between turns carried out in this work, and tests described in the literature have both shown that the line currents may reach values which sometimes may be detected by overcurrent relays or correctly dimensioned current limiting fuses. Consequently, adequate overcurrent protection against the most common type of internal faults in distribution transformers can not be achieved, neither with the implementation with primary circuit breaker and commercial overcurrent relays, nor with the fuse-loadbreaker combination. Tests with internal short circuits between turns have shown that gas-actuated Buchholz relays operate very satisfactorily and fast both for transformers with conservator and for hermetically-sealed transformers. Used together with a primary circuit breaker and a correct dimensioned overcurrent relay or a fuse-loadbreaker combination, the gas actuated relay seems to be the best safety arrangement for the most common type of fault in distribution transformers, namely short circuits between neighbouring turns or layers in the MV winding.

1. This accident is described in Appendix B.
2. The accident happened in Horten, Norway in 1982.

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LIST OF SYMBOLS

Most of the symbols used in the text are included in this list. There are, however, a few symbols not included because they occure rather locally and can hardly be mistaken for other quantities.

A, B, C	Transformer limbs or associated coils.
A_{core}	The cross section area of the core in the transformer model.
B_f	Magnetically flux density in the core of the transformer model.
E_{ph}	Applied phase voltage.
E_{line}	Applied line voltage.
E'_D	The e.m.f. induced the delta coil by leakage coupling.
E_P	Applied voltage to the primary coil.
E'_P	The e.m.f. induced in the primary coil by leakage coupling.
E'_1, E'_2	The e.m.f.'s induced in coils 1 and 2 by leakage coupling.
$E_{line,\Delta}$	The primary line voltage for the delta/star connected transformer.
$E_{line,Y}$	The primary line voltage for the star/star connected transformer.
i_A, i_B, i_C	The components of the magnetizing currents that are in phase α.
i'_A, i'_B, i'_C	The components of the magnetizing currents that are in phase β.
I_A, I_B, I_C	Primary currents in phase A, B and C.
i_a, i_b, i_c	The load currents in phase A,B and C, respectively.
I_D	Current in the secondary delta coil.
I_F	Fault current.
I_{F0}	The line current before the short circuit is established.
i_{f0}	Secondary load current before the short circuit is established.
I_{f1}, I_{f2}	Line current in the primary coil of the modell transformer
I_{k-j}	The current flowing from the transformer tank to earth.
$I_{m,N}$	Rated magnetizing current for the 300 kVA transformer.
I_N	Rated current.

$I_{N,P}$	The rated primary current for the model transformer, referred to the primary side.
I_S	Current in the short-circuited turns.
$I_{S,extr}$	Extrapolated value of the current in the short circuited turns with full supply voltage, based on measurements with a low supply voltage on the model transformer.
$I_{sc,pros}$	Prospective short circuit current.
I_Δ	The line current when the transformer is delta/star connected.
I_Y	The line current when the transformer is star/star connected.
$I_{2,P}$	The current in the short circuited part of the modell transformer referred to the prim ry side.
j	$\sqrt{-1}$
L_l	The inductance of a single-phase transformer wound on one limb with short-circuited turns.
L_{mn}	Mutual leakage inductance between coils m and n.
$m_{winding}$	The mass of one turn.
N_P	The number of turns in the undamaged primary coil.
N_S	The number of short-circuited turns.
N_D	The number of turns in the secondary delta coil.
n	$\frac{N_P - N_S}{N_S}$
P	Power.
p	Pressure.
p_{GA}	The pressure in the transformer when the alarm signal from the gas actuated Buchholz relay is actuated.
p_{GR}	The pressure in the transformer when the release signal from the gas actuated Buchholz relay is actuated.
p_{PR}	The pressure in the transformer when the alarm signal from the pressure actuated relay is actuated.
P_{loss}	The total copper loss in the coils.
$\mathcal{P}$	The permeance of the space occupied by the flux Φ.
$\mathcal{P}_{11}$	The permeance of the space occupied by the flux Φ_{11}.

$\mathcal{P}_{21}$	The permeance of the space occupied by the flux Φ_{21}.
$\mathcal{P}_{12}$	The permeance of the space occupied by the flux Φ_{12}.
$\mathcal{P}_{core}$	The permeance of the space occupied by the core flux Φ_{core}.
$\dot{\mathcal{P}}_{core}$	The permeance of the space occupied by the flux $\Phi_{\alpha A}$, $\Phi_{\alpha B}$ or $\Phi_{\alpha C}$.
$\ddot{\mathcal{P}}_{core}$	The permeance of the space occupied by the flux $\Phi_{\beta A}$, $\Phi_{\beta B}$ or $\Phi_{\beta C}$
q_{Cu}	393 $\left[\frac{Ws}{kgK}\right]$. Specific heat for copper.
R_1	The winding resistance of the primary coil for the transformer model.
$R_{2,P,T}$	The winding resistance of the secondary coil referred to the primary side at a temperature T for the transformer model.
R_{20}	The ohmic resistance at 20 ^{0}C.
R_m	Noninductive magnetizing resistance ("core losses").
R_{DP}	The winding resistance of one delta coil with N_D turns.
R_{NP}	The winding resistance of one primary coil with N_P turns.
R_{eq}	The equivalent series resistance.
R_{sc}	$R_1 + R_{2,P}$
$R_{winding,20}$	The ohmic resistance of one turn at 20 ^{0}C.
S_N	Rated power for the transformer.
t	Time.
T	Temperature in ^{0}C.
U_A, U_B, U_C	The primary voltage between the phase and the primary neutral for phase A, B and C, respectively.
U_{AC}	The primary line voltage between phase A and B.
U_{A-j}	Phase-ground voltage for phase A.
U_{A1-j}	Phase-ground voltage at point 1 for phase A.
U_{A3-j}	Phase-ground voltage at point 3 for phase A.
$U_{arc,1}$	$U_{B1-j} - U_{A1-j}$
$U_{arc,3}$	$U_{B3-j} - U_{A3-j}$

U_{B-j}	Phase-ground voltage for phase B.
U_{C-j}	Phase-ground voltage for phase C.
U_{B1-j}	Phase-ground voltage at point 1 for phase B.
U_{B2-j}	Phase-ground voltage at point 2 for phase B.
U_{B3-j}	Phase-ground voltage at point 3 for phase B.
U_{F0}	The volatage between one phase and the primary neutral before the short circuit is established.
U_{line}	Line voltage.
U_N	Rated voltage.
U_{N-j}	Voltage between the primary neutral and earth.
$U_{N,P}$	The rated primary voltage of the transformer.
U_P	Primary voltage.
U_S	Secondary voltage
u_r	The ohmic component of the short circuit voltage in %.
u_{sc}	Short circuit voltage in % for a transformer.
u_x	The inductive component of the short circuit voltage in %.
v_B	E.m.f. in phase α induced in phase B by the flux $\Phi_{\alpha B}$
v_C	E.m.f. in phase α induced in phase C by the flux $\Phi_{\alpha C}$
V_B	Total e.m.f. in phase α in phase B.
V_C	Total e.m.f. in phase α in phase C.
V'_A	Total e.m.f. in phase β in phase A induced by the flux $\Phi_{\beta A}$.
V'_B	Total e.m.f. in phase β in phase B induced by the flux $\Phi_{\beta B}$.
V'_C	Total e.m.f. in phase β in phase C induced by the flux $\Phi_{\beta C}$.
W_{in}	Total energy input in the transformer
W_{load}	Load energy in the ohmic load on the secondary of the transformer
$W_{magn,1}$	Average value of the field energy outside the core with a current I'_1 in coil 1.
$W_{magn,2}$	Average value of the field energy outside the core with a current I_2 in coil 2.

$W_{magn,12}$	Average value of the field energy outside the core with currents both in coil 1 and 2.
$W'_{melt,\,adiab}$	The energy needed to melt the winding by an adiabatic heating process
X_i	The reactance of a single-phase transformer wound on one limb with short-circuited turns.
X_m	Magnetizing reactance
X_{mn}	Mutual leakage reactance between coils m and n.
X_{sc}	$X_1 + X_{2,P}$
X_{0P}	The "zero-phase sequence reactance" of a primary coil in a star/star transformer.
X_{0D}	The "zero-phase sequence reactance" of a primary coil in a star/delta transformer.
X_{0S}	The "zero-phase sequence reactance" of the short circuited turns.
X_1	Primary leakage reactance.
$X_{2,P}$	The secondary leakage reactance referred to the primary side.
Z_{sc}	The short circuit impedance of the transformer.
α, β	Vector phases.
α_{Cu}	0.00392 K^{-1}. The temperature coefficient for copper.
λ_1	The flux linkage for coil 1.
λ_2	The flux linkage for coil 2
Φ_A	Core flux in limb A.
Φ_{AB}	Core flux circulating between limbs A and B.
Φ_{BC}	Core flux circulating between limbs B and C.
Φ_{CA}	Core flux circulating between limbs C and A.
$\Phi_{\alpha A}$	Phase α component of Φ_A.
$\Phi_{\alpha B}$	Phase α component of Φ_B.
$\Phi_{\alpha C}$	Phase α component of Φ_C.
Φ_{1l}	The flux produced by I_1, which links only the $(N_P - N_S)$ turns in coil 1.
Φ_{2l}	The flux produced by I_S, which links only the N_S turns in coil 2.
Φ_{12}	The leakage flux induced by coil 2, which links only with coil 1.

Φ_{core}	The "core flux", whose path is entirely in the iron circuit.
Φ_1	The total flux linking coil 1.
Φ_2	The total flux linking coil 2.
ω	$2\pi f$, where f is the frequency in Hz.

1 INTRODUCTION

Higher load densities, accompanied by larger substations, shorter feeders and cable-connected primaries have increased the power and energy delivered by a power system to a low-impedance fault in MV networks. In such networks, a variety of protection devices is used to protect equipment and personnel. Distribution transformers are main components in such systems, and special attention must be paid to protection schemes. Distribution transformers ratings usually range from 50 to 2000 kVA, with primary voltages from 6 to 36 kV (usually denoted as medium voltage). Most of the transformers are mineral-oil-filled, and the transformer tanks are either open systems with conservator, or hermetically sealed systems.

Traditionally the distribution transformers have been protected against primary and secondary faults by expulsion fuses or current limiting fuses[1]. The service experience with these devices has been fairly good [1].

With the introduction of SF_6 insulated switchgear, the application of fuses in a manner which maintains the same level of immunity to environmental effects as the switchgear itself, causes problems. With switchgear that includes MV fuses for transformer protection, there exists a need to gain access to the fuses for replacement. Suitable methods have been devised to provide this access, taking into account the factors of heat transport, aging, sealing against humidity and pollution, mechanical tripping of associated switches, interlocking and earthing, easy and safe fuse replacement, and an optimum arrangement for the fuses and their containers [2].

The introduction of MV switchgear incorporating simple circuit breakers for transformer protection has re-opened the discussion of protection philosophy. Comparison of circuit breaker based protection with the widely used fuse based protection will be a main subject.

Even with maximum care in design and manufacturing, some distribution transformers will fail as a result of normal thermal aging of insulation or abnormal service conditions. The service experience and fault statistics of distribution transformers in cable networks show that the failure rate of these transformers is less than one per thousand per year. Given the low number of transformers presently being damaged, it is obvious that the expense of transformer protection can not be justified. It is also obvious that the overcurrent and fault-current protection of the transformers only prevent destruction of the transformers to some extent. To protect the transformers against overvoltages, it is desirable to have some kind of overvoltage protection. The approach to this problem is outside the scope of this work.

With overcurrent and fault-current protection of the distribution transformer, other electrical equipment will also be indirectly protected. With the same argument as above, the reduced expenses related to damaged electrical equipment can not be justified by the increased expenses for the transformer protection. For instance, if the transformer is installed inside a building, this

1. At low to moderate fault currents the expulsion fuses offer rapid operation because - unlike current limiting fuses - the element has a small surface area and is not surrounded by thermally conductive filler. At higher fault currents, because the element lacks limiting restrictions, operation is much slower than for current limiting fuses [3], [4].

may justify the increased expenses of transformer protection.

Another criteria for transformer protection may be that line lockout in the distribution system should be prevented in the event of a transformer failure. But the reliability of the fuse-load-switch combination is probably lower than the reliability for distribution transformers installed in the cable network, defeating the above-mentioned argument.

From the preceeding discussion, it is clear that the main arguments for the overcurrent and fault-current protection of distribution transformers are not based on economic or reliability considerations. The main argument for overcurrent and fault-current protection is to ensure the safety of the general public and operating personnel by protecting against explosions or transformer tank rupture

As a summary, the following conditions should be addressed by the transformer protection:

- faults between the MV switchgear and the transformer
- internal faults in the transformer
- faults between the transformer and the LV busbar
- overload currents exceeding certain limits

Main objectives of the present work:

- Study of different mechanisms of faults in distribution transformers.
- Find the most likely type of transformer faults.
- Give a better understanding of what is happening both physically and electrically when there are internal faults in distribution transformers.
- Study how different protection schemes will handle different kinds of transformer faults.

Organization of the thesis:

Chapter 2 presents a literature survey of theories, hypotheses, assumptions and experiences with failures and their causes in transformers. Different fault statistics about transformer failures are also presented in this chapter. A survey of experiments with different kinds of faults in oil-filled transformers described in the literature is presented in chapter 3. Chapter 4 presents some calculation models for currents due to faults between turns in transformer windings. The calculation models are based on a report found in the literature [5]. In the last part of this chapter, section 4.7, results from measurements carried out in the laboratory are used together with the equations evolved with the calculation models.

Chapter 5 deals with tests of short circuits between turns on a single-phase transformer model. Based on these tests, electrical equivalent circuits are developed for the transformer which are

valid for different fault conditions. In chapter 6, gas generation under different fault conditions is studied, based on the tests from chapter 5. The first part of this chapter is based on a literature survey, and section 6.4 is based on experiments carried out in the laboratory.

In chapter 7, full scale tests with short circuits between turns in three-phase distribution transformers were carried out, based on the results from the model tests. Chapter 8 describes full scale tests with internal power arcs between MV phases in distribution transformers. Most of the details from the tests in chapter 7 and chapter 8 could have been placed in the appendix. But the tests described in these chapters required great preparations, and the tests were very expensive to carry out. Because of this it was decided to present the tests entirely in the main report

A brief survey of distribution substations and switchgear is presented in the first part of chapter 9. The second part gives a brief survey of how distribution transformers are protected today. A comparison of different types of distribution transformer protection is given in section 9.6. The discussion and comparison of different protection schemes is mainly based on tests with internal transformer faults described in chapters 7 and 8, and on results from different transformer tests described in the literature, chapter 3.

The main discussion in this thesis is given in chapter 10, and chapter 11 presents a short conclusion.

Appendix A gives a brief survey of the design of different distribution networks. Appendix B describes a recent occurrence of a transformer failure, where evolved gases subsequently led to an explosion of the substation.

2 MECHANISMS OF TRANSFORMER FAULTS

2.1 SUMMARY

In considering the best way to protect a distribution transformer, it is necessary to have an idea of the statistical probability of the possible failure modes. In [2] considerable effort has been expended in seeking users information of the incidence of various types of transformer faults in Europe. The information concerning the causes and sites of damage for internal faults was small. It is said that the main reason for the scarcity of information was given as the extremely low number of faults. In this chapter a survey of theories, hypotheses, assumptions and experiences with failures and their causes in transformers will be given.

The great majority of internal failures in distribution transformers starts as insulation faults and short circuits between neighbouring turns or layers of turns in the windings [6], [7], [8], [9], [10], [11], [12], [13]. The majority of faults start in the MV winding. The insulation failures can be triggered by factors as thermal failures, mechanical stresses, electrical failures or aging processes. Studies of records of transformer breakdown have shown that about 70-80% of the number of failures may be traced back to short circuits between turns [13].

The great majority of the short circuits between turns are progressive [2], [9], [11], [14], [15]. This means that the fault starts as a short circuit between neighbouring turns or turns of layers, and then gradually involves more and more turns. Electrical contact between two adjacent turns of wire will cause a high current to flow through the turns involved. The local heat generation may lead to further damage, and the fault may involve more turns. The development depends on such factors as the construction and connection of the windings. It also depends on where in the winding the short circuit originates, and the amount of cooling by oil. Excessive currents flowing in transformer windings will also produce large mechanical stresses. When a distribution transformer has been exposed to this type of fault, it is as a rule very difficult to determine what has caused the failure, since all evidence is eliminated by the very nature of the breakdown.

The fault rate for distribution transformers in the overhead line distribution network in Norway varies comparatively much from year to year because it depends much on the frequency of thunderstorms. The mean fault rate of these transformers are found to be about 1.85 faults per 100 transformer years. There is no written information or statistics of the fault rate for ground mounted, cable connected distribution transformers in Norway. Based on fault statistics from Germany, Holland and The United Kingdom it is supposed that the fault rate for distribution transformers in the cable network is less than 0.1 faults per 100 transformer years.

2.2 A HYPOTETICAL MECHANISM OF TRANSFORMER FAILURE

Figure 2.1 shows the causes and series/combination of events leading to failure or explosions of transformers presented in [15].

Distribution transformer explosions are usually the result of high internal pressure build-up caused by energy released by electrical arc or ignition of combustible gases due to insulation

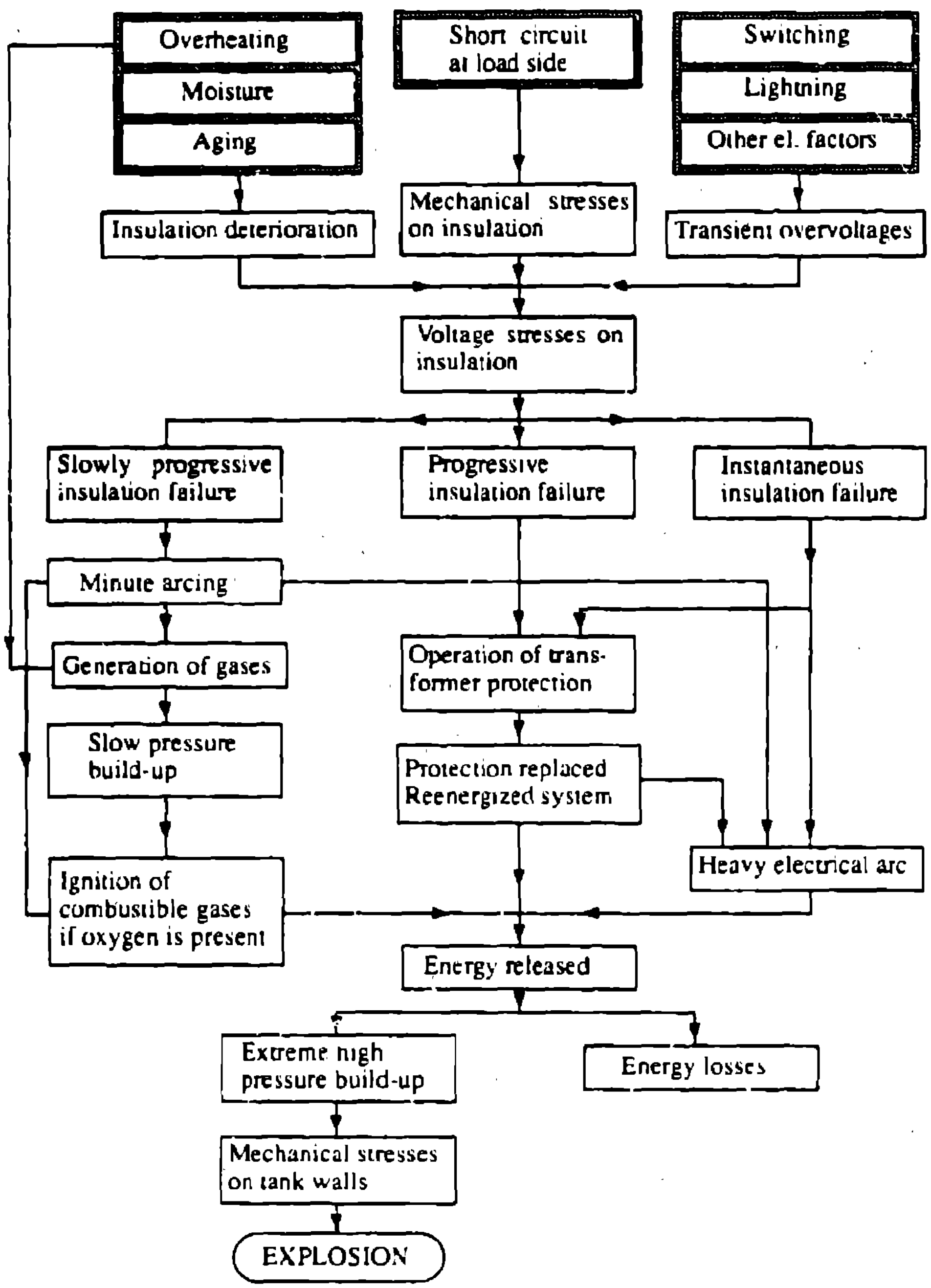


Figure 2.1 Hypotetical mechanism of transformer failure. The figure is mainly based on reference [15]

failures triggered by any of the following[1] [15]:

- Insulation deterioration due to the combined effect of aging and moisture penetration.
- Mechanical stresses on solid insulating material caused by momentary and sustained short circuit in the connected load.
- Voltage stresses on insulation materials caused by transient and sustained overvoltages.

Depending on the cause, insulation failure may be either slowly progressive, rapidly progressive or instantaneous. The possibility of explosion of the transformer is mainly determined by the internal pressure developed, which depends on the amount of energy released when an insulation failure occurs inside the transformer tank.

2.3 BASIC REASONS FOR TRANSFORMER FAILURES

2.3.1 Thermal failures

Failures in the magnetic circuit [13], [16]:

- There is reported breakdown of the insulation around the bolts inserted through the cores and yokes for the purpose of clamping the laminated core[2]. This causes local short circuits paths, producing intense local eddy currents.
- Failures may also occur of the insulation between laminations and of the insulation between yokes and yoke clamping plates.
- The edges of the core and the yoke laminations may have become burred during manufacture. The burrs will produce local short circuits in the iron laminations, and eddy currents with consequently abnormal heating will occur.
- Metallic filings between the laminations are liable to produce intense local eddy currents and excessive local heating of the core in the transformer.

Badly made joints between coils [13]:

Such joints may overheat on load. The heat generated at the joint will probably be transmitted to a length of the conductor of each coil. This may partially carbonize the insulation round the conductors, and eventually result in a short circuit between turns.

External short circuit on the secondary side:

This may lead to overheating of the conductors, further leading to damage of the insulation resulting in an internal short circuit.

1. Then also oxygen must be present.
2. This construction with bolts through the cores and yokes is not used anymore.

Heavy overload [13], [17]:

Sustained heavy overload produces high temperatures throughout the transformer. The coil insulation becomes brittle and weakened and in time probably flakes off the conductors in spaces, and short circuits between turns can be established. In [17] it is said that the insulation can be carbonized enough to cause a fairly high leakage current to flow. This leakage current further deteriorates the insulation.

2.3.2 Mechanical stresses

Vibrations [2], [13]:

If the core-structure clamping bolts are not locked effectively, vibrations during delivery or in service will be set up and tend to weaken the core insulation and produce failures similar to those outlined in section 2.3.1.

Movements of parts of the coils [6]:

During short circuits on the secondary side of the transformer the fault currents on the primary can be $20 \times I_N$ when $u_{sc} = 5\%$. This will result in large forces on the windings. New transformers are designed to withstand this short circuit test. In a new transformer, however, the insulation and the mechanical structure have not been weakened by aging. In [17] it is said that there is increasing evidence that transformers may succumb to repeated faults of relatively low magnitude even though they have successfully withstood a single high magnitude secondary short circuit fault. It is said that in cases where transformers have failed as a result of external faults, this is usually because coils or parts of coils have been displaced by the fault current. Breakdown may not occur immediately after the turns are displaced, but should the transformer vibrate while on load due to looseness of core bolts, or should it receive repeated heavy electromagnetic shocks, abrasion of the insulation between adjacent dislodged turns may result in internal short circuits [13].

Rapidly fluctuating loads [13], [18]:

If a transformer is subjected to rapidly fluctuating loads, the expansion and contraction of the winding conductors alternately increases and decreases the mechanical pressure on the insulation between turns. As the dielectric strength of most insulation decreases with increasing mechanical pressure, the winding becomes more susceptible to failure if it is subjected to electrical or magnetic shocks.

2.3.3 Electrical failures

Steep fronted surge voltages:

Steep fronted surge voltages are the most common cause of electrical breakdown followed by immediate short circuit or the creation of electrical discharges leading to later breakdown [2]. In [15] it is found that most of the transformer faults occur during months with relatively high frequency of lightning. Surge voltages caused by lightning normally occur only in overhead systems, meaning that transformers situated in underground cable networks do not normally be

exposed to surge voltages caused by lightning [19]. The excessive voltages set up by surges may be accentuated at open-ended tappings, at any point of change of surge impedance in the winding.

Switching out of unloaded transformers:

When switching out an inductive winding, such as a transformer primary side with the secondary side open-circuited, the magnetizing current and consequently the magnetic flux will decrease rapidly. The electromagnetic energy stored in the transformer becomes rapidly dissipated, giving high voltage rises as a result. The induced voltage rises are dependent upon the rate of change of magnetic flux and not upon the actual value, so that severe voltage rises may occur when the flux is subjected to a rapid change at any point on the wave. The rapid cooling of the interrupting arc in switches, particularly during the last half-cycle, has been found to augment this effect.

These switching overvoltages generally become manifested by flashovers on the transformer terminals and by short circuits between turns of the windings resulting from the puncture of the insulation between them. The switching out voltages are not prevalent [13].

Corona:

Corona may take place from sharp conducting edges or small diameter conductors if the surface voltage gradient is high [13].

Insufficient clearance between the phases:

Short circuits between phases may occur if there is insufficient clearance between the phases. This may sometimes be aggravated by the insertion of a pressboard barrier between phases if the presence of the barrier upsets the distribution of dielectric stress to such an extent as to put too high stress across the oil spaces and across the barrier [13].

2.3.4 Aging processes

The decline in quality of insulation during the aging process limits the life of the transformer. The aging process can be slow and involves a weakening of the insulating and mechanical properties. In a distribution transformer the following components may be involved in the aging process: the oil, the paper insulation, the pressboard barriers, the insulation varnish and other insulation materials used in the transformer. The aging phenomena involve both physical and chemical changes [18], [20]:

The physical effects may be ascribed to:

- melting due to excessive temperature
- softening
- volatilization
- cracking
- decrease of tensile strength

- decrease of dielectric strength.

The chemical effects may be ascribed to:

- oxidation
- depolymerization
- hydrolysis

Moisture will decrease the dielectric strength of transformer oil and also increase its acidity [13], [21]. Deterioration of the oil may also occur as the result of prolonged overloading of the transformer, and excessive oil temperature accelerates the formation of sludge, water and acids [13].

2.3.5 Other reasons

Transformer failures may also occur as a result of:

- Undetectable deficiencies in materials of workmanship [13], [21].
- Misapplications [21].
- Abnormal service conditions [21].

2.4 MECHANICAL EFFECTS OF INTERNAL FAULTS IN TRANSFORMERS

Excessive currents flowing in transformer windings produce large mechanical stresses. Excessive currents can be caused by external short-circuit and switching currents, or by internal short-circuits in the windings. Owing to the concentration of large current within a small space, the forces and stresses involved are usually much more severe than in the cases previously considered. They are likely to result in permanent deformation, decrease of clearances, and subsequently breakdown [22].

2.4.1 Radial forces

When a concentric transformer winding is subjected to an external short-circuit across the terminals of the secondary winding, the whole flux corresponding to the supply voltage at the terminals will pass through the duct between the primary and the secondary winding and give rise to a repulsion between them.

The magnitude of the radial force tends to press the inner winding against the core and stress the outer winding like the walls of a cylindrical container under internal pressure [23].

2.4.2 Axial forces

If the two windings are perfectly symmetrical, the only force acting on each coil is the radial pressure. This is counteracted by the tensile strength of the conductors in the outer winding and the resistance to crushing of the inner winding. The primary and secondary windings are, however, in a state of unstable equilibrium in the axial direction. This is shown in Figure 2.2.

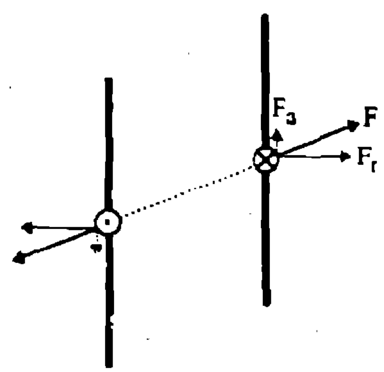


Figure 2.2 Unstable equilibrium between transformer windings.

If the magnetic centre of one winding is displaced axially with respect to that of the other, an axial force will be active and tends to increase the displacement. The repulsive forces are pictured as acting between the magnetic centres of the two windings. This simplification would lead to a wrong estimate of the force, but it shows that the equilibrium is unstable. This force is approximately proportional to the displacement and is of considerable magnitude even for small values of the displacement [23]. In Figure 2.2 this force is called F_a.

2.4.3 Internal short circuit

When an internal short circuit occurs, the distribution of the magnetic flux is fundamentally altered. The short-circuited part of the winding acts like a short-circuited secondary of an auto-transformer, the primary of which is the main body of the faulty winding still remaining in circuit. The entire core flux corresponding to the voltage maintained across the terminals of the winding again passes as leakage flux between the two parts of the winding, but this time mainly in a radial direction. The radial direction of the flux gives rise to a large axial repulsion between the two parts which, acting on the conductor, strains it in an axial direction [22], [23]. The forces are then transmitted through the insulation material between turns and finally act as end thrust on the clamping gear, which is stressed accordingly.

Even if the current drawn from the line can be small, very large currents can circulate in the short-circuited turns. An electromagnetic force, which pushes the coil away from the centre of the remaining part of the winding, will be set up since the current flows in opposite directions through

the two parts of the winding. This force is small if the short-circuited turns is located near the centre of a uniform winding, and large if the short-circuited part of the coil is near the end of the winding.

2.4.4 Effect of core saturation

As the fault involves an increasing number of turns it leaves fewer turns in circuit across the supply voltage if the transformer is delta-connected. If the transformer is star coupled, the voltage across the two other phases is increasing considerably. The core will be more and more saturated when the number of short-circuited turns is increasing. Consequently the windings will draw excessive magnetizing currents, giving rise to large additional forces. In extreme cases the currents can be limited more by the reactance of the supply system than by the transformer itself and will approach in magnitude the short-circuit current at the primary transformer terminals [22].

2.5 DEVELOPMENT OF THE FAULT

As described in section 2.2, the great majority of failures start as faults between turns or layers of turns in the windings. In section 2.3 some basic reasons for transformer failures were described. This section will deal with the development after the fault has been initiated.

2.5.1 Short circuit between turns or layers

The great majority of the short circuits between turns are progressive [2], [9], [11], [14], [15]. The fault may start as a short circuit between two neighbouring turns or layers, and the short circuit gradually involves an increasing number of turns. Since most of the winding impedance remains in the circuit, the initial fault current is relatively small. As the damage extends to larger parts of the winding, the winding impedance decreases and the primary current increases. The degree of increase depends on factors as the construction, connection and the amount of cooling by oil of the windings, see chapter 4.

The windings may be constructed in different ways:

- In the disc winding the winding consists of a number of discs wound continuously from a single wire or a number of strips in parallel. Each disc consists of a number of turns wound radially over one another, the conductor passing uninterruptedly from disc to disc. The insulation between the coils is usually very good, and the fault will probably be limited to one or two coils [2].
- A winding of the continuous layer type consists of a number of layers of wire wound along the whole core. A fault in this type of winding can evolve quickly since a fault between layers will quickly involve a substantial proportion of the whole winding.
- In a winding of the crossover type, the crossover coils are wound on formers and each coil consists of a number of layers having a number of turns per layer. It is not usual to apply any extra insulation to the conductor itself in this type of coil apart from the conductor varnish

or the paper covering. Between layers it is customary to use one or two layers of some flexible insulation such as paper. The insulation between layers is usually wrapped around the end turn of the layer, thereby assisting to keep the whole coil compact. The complete winding consists of a number of such coils in series. They are spaced apart by means of insulating key sectors. Compared to the winding of the continuous layer type the number of turns per layer is reduced. A short circuit between two neighbouring layers does not include as many turns as may occur in the continuous layer type. But anyway, the fault can quickly involve a substantial portion of the faulty crossover coil, as the resistance against high temperature and burn through is low for the layer insulation.

In the literature different causes are given for how a short circuit between two turns may develop such that more turns will be involved:

- Electrical contact between two adjacent turns of wire will cause a high current to flow through the turn involved. If the contact resistance is ignored, the current in the short-circuited turn is approximately equal to the quotient of the voltage per turn and the resistance of the wire [2]. As the resistance of one turn is quite low, the fault current can be several kA. The local heat generation then leads to further damage and the fault may involve more turns. The development depends on a number of factors as mentioned earlier (transformer connection, winding construction etc.).
- In [6] and [11] it is said that arcing faults generally start as short arcs or incipient faults, such as faults between turns or layers in the transformer windings. Arcs may be established by melting of the winding wire in the event of a fault [2]. Arcing at the initial failure point causes the failure to spread to adjacent turns or layers [6]. The initial arcs in the winding decomposes the surrounding oil and insulation into hot, volatile and ionized gas. The stage is set for more violent faults, since a flashover from a high potential to ground may occur through the ionized gas bubbles [11].

2.5.2 Flashover through gas bubbles

An arc in transformer oil decomposes the surrounding oil and insulation into hot, volatile ionized gases. (See section 6.2). The gas mixture is non-condensable and flammable/explosive if oxygen is present. These gases also have a low dielectric strength and are therefore liable to cause breakdown between live parts in the vicinity of the arc [7]. The low dielectric strength and the non-condensable property of the gases can cause a relatively minor arc to become a major fault if the evolved gases envelop the major insulation causing a breakdown of the line to ground or the line to line insulation system [7], [11].

2.6 FAULT STATISTICS

Statistics for faults with distribution transformers will be presented in this section. The fault statistics are from Norway, Germany, Holland and The United Kingdom. The numbers placed above the columns in Figure 2.3, Figure 2.4 and Figure 2.5 are the total number of transformers included in the statistics.

2.6.1 Fault rate for distribution transformers in the overhead line distribution network in Norway

The transformers included in the statistics in Norway are all situated in the overhead line distribution network [24]. It is assumed that most of the failures here are caused by lightning overvoltages. See Figure 2.3.

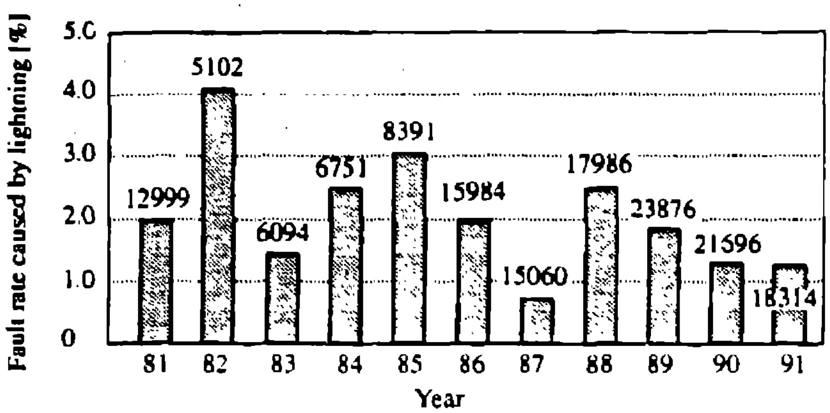


Figure 2.3 The failure rate of transformers in the overhead line distribution network in Norway caused by lightning for the period 1981-1991 [24].

The transformers in these examinations are 12 and 24 kV transformers. The fault rate varies considerably from year to year. In the period 1981-1991 the average fault rate for the transformers that are included in the statistics is 1.85%. Of cause the fault rate is very dependent of the frequency of thunderstorms and lightning.

2.6.2 Fault rate for distribution transformers in Germany

Fault statistics from Germany in 1985 is described in [25]. Figure 2.4 shows the main results.

It is seen that the fault rate increases with the rated primary voltage for the transformers. The average fault rate for the transformers in the overhead line and cable networks is 0.147%. For the transformers in the cable networks the mean fault rate is 0.085%.

2.6.3 Fault rate for distribution transformers in the cable network in Holland

Fault statistics from transformers in cable networks in Holland is shown in Figure 2.5

In the period 1987-90, the average fault rate was 0.075% per year.

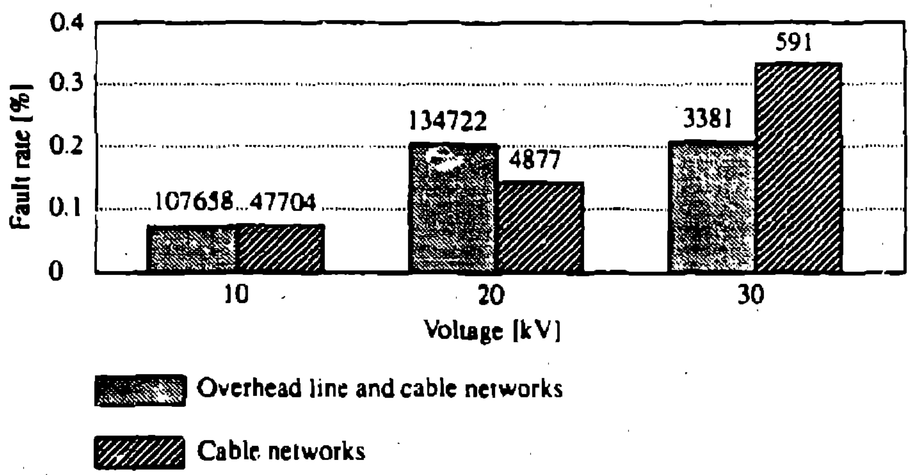


Figure 2.4 The failure rate based on data from Germany for transformers placed in overhead lines and in cable networks in 1985 [25].

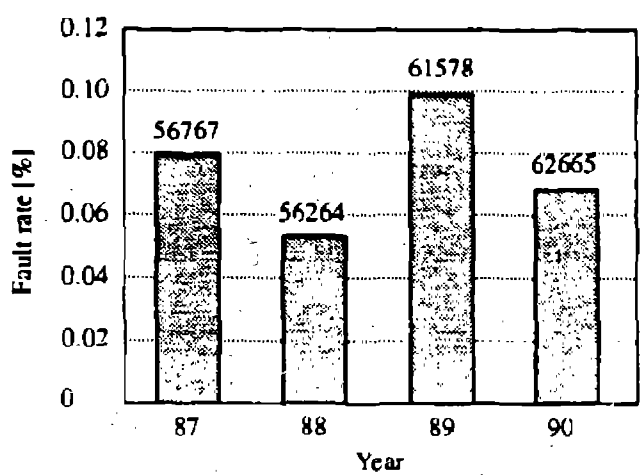


Figure 2.5 The failure rate of transformers placed in the cable distribution network in Holland for the period 1987-1990 [26]

2.6.4 Fault rate for distribution transformers placed in the cable network in The United Kingdom

A survey of the fault possibilities in the statistics:

In the usual arrangement for the connection of distribution transformers in the distribution system,

an analysis of the fault possibilities can be considered for three main zones [27];

Zone A: the region between the transformer and the HV switchgear
Zone B: the transformer itself
Zone C: the region between the transformer and the LV fuses which protect the LV feeders.

Inside the transformer the possible fault zones can be further sub-divided as illustrated in Figure 2.6.

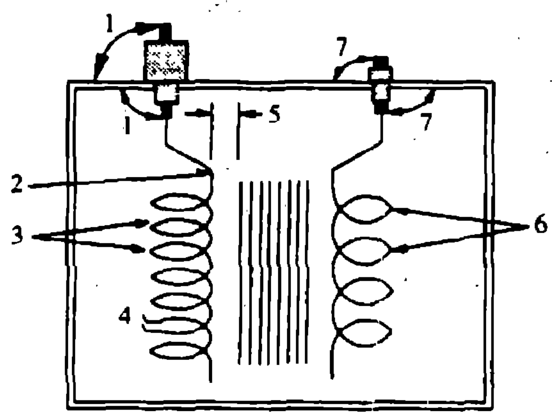


Figure 2.6 Possible fault areas in a distribution transformer [27].

Referred to Figure 2.6 the possible fault sites are:

1. High voltage terminals.
2. High voltage connection fracture.
3. High voltage winding failure.
4. Tap changer failure.
5. High voltage insulation failure.
6. Low voltage winding failure.
7. Low voltage terminals.

From the results in Table 2.1 it is seen that faults in sites 1 and 2 are virtually non existent. Similarly, faults in the tap changer (site 4) are found to be extremely rare, and those occurring are most often mechanical in origin. This leaves us with consideration of insulation failure at sites 3, 5, 6 and 7. The principal differences here lie with the size and development of the fault current [27].

Table 2.1 summarizes the ESI (Electricity Supply Industry) fault statistics for ground mounted,

cable connected distribution transformers in the period 1984-1989 in the U.K. [27].

Component where fault occurred	%age of all faults	Fault rate in [%]
Cable terminations	38.5	0.069
Other external connections	7.5	0.013
Windings and connections	29.3	0.052
Tanks, radiators etc. (mostly corrosion)	8.6	0.015
Tap changers, mechanical faults	3.2	0.006
Tap changers, electrical faults	0.5	0.0008
Other sites, mostly accessories	4.4	0.008
Unknown, presumably because site destroyed	8.0	0.014
TOTAL	100.0	0.178

Table 2.1 Fault statistics for ground mounted, cable connected distribution transformers in the U.K. in the period 1984-1989 [27].

The average number of transformers included in the statistics over the years 1984-1989 was 163500. It is seen that most of the faults are in the cable terminations and in the windings and connections. It is seen that the total fault rate was 0.178%, or 1.78 faults per 1000 transformers per year.

In [28] it is said that for ground mounted 11/0.433 kV distribution transformers, approximately 100 transformers fail per year out of a total of 160000.

2.6.5 Comparison of the fault statistics

The fault statistics for transformers in ground mounted, cable connected distribution transformers from Germany, Holland and The United Kingdom is shown in Table 2.2. It is seen that the fault rate in the United Kingdom is larger than in Germany and Holland. One reason for this may be that faults in the cable terminations is not included in the statistics in Germany and Holland. (The sources say nothing about this, it is just an assumption). If the faults in the cable terminations are removed from the fault statistics, the fault rate will be about 0.1% in The United Kingdom.

It is seen that the fault rate for transformers in the overhead line distribution network in Norway is 10-20 times the fault rate for transformers in cable networks in Germany, Holland and The United Kingdom. There is no written information or statistics about the fault rate for ground mounted, cable connected distribution transformer in Norway. It is natural to assume that the fault rate for these transformers is about the same in Norway as in the other countries mentioned above.

Country	Number of transformer-years	Fault rate [%]
Germany [25]	53172	0.085
Holland [26]	237274	0.075
United Kingdom [27]	~981000	0.178

Table 2.2 The fault rate in three countries for ground mounted, cable connected distribution transformers.

Communication with people working in different Norwegian electricity boards confirm that the assumption about that the fault rate for distribution transformers in the cable network in Norway is less than 0.1%.

2.7 CONCLUSIONS

Based on fault statistics from Germany, Holland and The United Kingdom, it is assumed that the fault rate for distribution transformers in the cable network is less than 0.1 fault per 100 transformer years.

The great majority of distribution transformer failures start as faults between turns or layers in the MV-windings. Some basic reasons for this kind of transformer failure can be listed as:

- Thermal failures
  - failures in the magnetic circuit
  - badly made joints between coils
  - external short circuit on the secondary side
  - heavy overload
- Mechanical stresses
  - vibrations
  - movements of parts of the coils
  - rapidly fluctuating loads
- Electrical failures
  - steep fronted surge voltages
  - switching off unloaded transformers
  - corona
  - insufficient clearance between the phases
- Aging processes
  - physical and chemical changes

Electrical contact between two adjacent turns of wire will cause a high current to flow through the

turns involved. The local heat generation then leads to further damage, and the fault may involve more turns. When the damage extends to more and more of the winding, the primary current increases. This evolution depends on such factors as transformer connection, winding construction etc.

Even if the current drawn from the line is small, very large currents can circulate in the short-circuited turns. This gives an electromagnetic force which pushes the coil away from the centre of the remaining part of the winding, since the currents flow in opposite directions through the two parts of the winding. When the core becomes more and more saturated, the windings will draw excessive magnetizing currents, giving rise to large additional forces.

3 A SURVEY OF EXPERIMENTS WITH INTERNAL FAULTS DESCRIBED IN THE LITERATURE

3.1 SUMMARY

This chapter deals with tests with internal faults in distribution transformers described in the literature. A large part of the literature deals with arcs inside American pole- or ground mounted distribution transformers. This type of transformers differs quite much in design compared to the transformers commonly used in Europe.

Three different types of distribution transformers will be described as an introduction. A brief repetition of some tests described in the literature with internal faults in distribution transformers will be given. The presentation is divided in four parts:

- tests with faults (mostly arcs) in American distribution transformers
- tests with generation of gas bubbles under different overload conditions in distribution transformers
- tests with internal short circuits between turns in a model transformer
- full scale tests with internal faults on European distribution transformers

From the tests with arcs in American transformers it was found that arcs in the transformers caused almost immediate decomposition of the surrounding oil into combustible and noncondensible gases and propagation of a shock wave through the remaining body of the oil. A wide range of fault power and energy was observed even for the same levels of available fault current, thus showing the difficulty in defining a typical fault. One important result was that faults contained within the winding produced less pressure in the transformers than an open arc, even for similar arc energies. In much of the literature it is said that long arcs drawn in oil represents an extreme worst case rather than the usual internal fault. The major factor affecting the arc voltage magnitude was found to be the arc length. It was determined that the voltage gradient is approximately 88 V/cm for open arcs in oil [11]. Pressure relief devices is only effective for slow-rising pressures due to low-level faults.

Tests with generation of gas bubbles under different overload conditions have also been studied by some researches The results showed that gas bubbles appeared to originate from within the coil and its insulation when the conductor temperature exceeded about 145 °C. The primary source of bubbles are supposed to be moisture. Bubble emission can also be caused by cooling of the transformer, but the intensity of bubble emission during rain fall was very dependent on the load current.

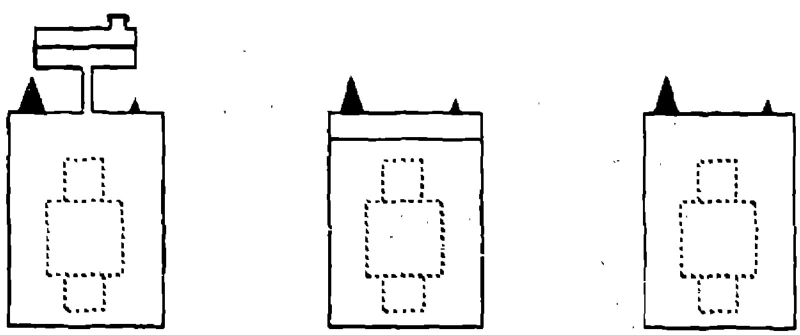
Tests with internal short circuits between turns in a model transformer are described in [2]. The tests showed that the conductor insulation can be destroyed, and the wires can melt because of the large current that will arise when turns are short-circuited in a transformer winding. It was also concluded that it is a realistic probability that an arc produced by the melting of the winding wire in the event of a fault will be extinguished due to the excellent arc extinguishing and cooling

properties of the transformer oil.

From the tests with internal faults in European distribution transformers large variations was found concerning how fast the MV insulation failure develops further. The speed of fault evolution depends on the winding construction and the site of the initial breakdown. Some tests also showed that when the faults developed to be a full short circuit, this happened extremely fast.

3.2 A DESCRIPTION OF DIFFERENT TYPES OF OIL FILLED DISTRIBUTION TRANSFORMERS

In the literature principally three different types of distribution transformers are described. The main difference is the construction of the transformer tank with regard to the expansion of the oil. The transformer insulating liquid is subject to changes in volume due to fluctuations in temperature and load. Gas formation during faults in the transformer must also be taken into account when the tanks are constructed. Open systems leave space for oil to expand, and in hermetically sealed systems, pressure fluctuations occur in the tank, which require special structural measures. Figure 3.1 shows the three characteristic sealing systems for the insulating liquid in distribution transformers.



(a) (b) (c)

Figure 3.1 Characteristic sealing systems for the insulating liquid in distribution transformers.
(a) Open system with conservator.
(b) Hermetically sealed system with gas cushion between the insulating liquid and the top of the tank.
(c) Hermetcally sealed system without gas cushion, variable-volume tank.

3.2.1 American distribution transformers

In much of the literature studied in this work, the transformers are of the so-called first generation transformers. See Figure 3.1(b). In this type of transformers, the design provide for a gas cushion, preferably nitrogen, as a compressible medium between the surface of the liquid and the top of the tank to absorb the pressure. In this transformers the gas pressure is due to four main components. The insulating oil is heated by the power loss in the transformer, expands to occupy space

otherwise taken by the gas cushion, and transfers heat to the gas. Both the heating of the oil and the heating of the gas, have the effect of increasing the pressure. In contrast, the change of volume of the tank and dissolving of gas in oil, will reduce the pressure.

The rated power of the American transformers described in the literature used in this work was mostly less than 100 kVA, and many of them were also single phase. The transformer can be of the so called pole-type or of the pad-mounted transformer. The first one is, as the name indicates, mounted on a pole in the overhead distribution network, and it is usually cylindrical. The pad mounted transformer is usually used in residential underground distribution systems, usually formed as a box. The pole-mounted and the pad-mounted transformers are otherwise of the same family of design.

3.2.2 European distribution transformers with conservator

This type of transformer is often called the second generation transformer. The open system with conservator is the one currently in general use. See Figure 3.1(a). The favorable effect exerted by this system on the aging of the insulation materials is due to the low temperature in the insulating oil in the conservator which slows down the entry of oxygen into the oil [29].

3.2.3 European hermetically sealed distribution transformers

This type of transformer is often called the third generation transformer. The aging of insulation materials is most effectively prevented by hermetically sealed systems. In the most used hermetically version today, the insulating liquid is enclosed without any gas cushion. The tank is of a flexible design, and it can expand and contract without damage according to the volume of the liquid. See Figure 3.1(c). The flexible elements are the individual corrugations of a corrugated-wall tank. The corrugations bulge outwards as the pressure increases and bulge inwards as the pressure falls.

3.3 TESTS ON AMERICAN POLE-MOUNTED AND PAD-MOUNTED DISTRIBUTION TRANSFORMERS

In the sixties and seventies much research was done on small distribution transformers in the U.S. The reason for this was the occurrence of violent failures with overhead distribution transformers. Arcing faults in the transformers often resulted in a cover blow-off of pole-type transformers or tank rupture on welded tank designs [9], [15], [17], [30], [31]. The amount of damage to the transformer itself was not a consideration, only the hazard to life and property was of concern [11], [31]. The cover blow-off or tank rupture sometimes led to blowout of hot and burning oil. The increasing fault energy delivering capability led to increased concern on both manufacturers and users about the possibility of disruptive failure of internally faulty distribution transformers [9], [17], [21], [32]. The arguments mentioned above were the main reasons for the research on transformer failures. The purpose of the research work was to get information about the reasons for the violent failures, and to find methods to prevent the disruptive failures.

3.3.1 Test conditions

The tests were done as full scale tests on transformers with rating from 10 to 100 kVA. All the transformers were of the type with a gas cushion between the insulating oil and the top of the tank as described in section 3.2.1. In some of the tests only the transformer tank without the core and windings was used. In some of the tests the transformer tanks were equipped with pressure relief devices.

To prevent the occurrence of disruptive failure, either the failed transformer must be able to contain the fault energy without disturbance, or the fault energy must not be allowed to enter the faulty transformer [21].

In the tests described in the literature it was examined how much energy input the transformer can bear without tank rupture. Mechanisms leading to tank rupture were studied, together with the significance of where the primary arcs were drawn. The effectiveness of pressure relief devices was also examined. Tests with different types of fuses in series with the transformers to prevent the disruptive failures were also done.

In many of the tests the purpose was to simulate arcing faults inside the transformer. Primary arcs were drawn by mounting either a thin bare wire or an oil immersed expulsion fuse at various depths below the oil surface [10]. Tests were done with arcs between phase and earth, or arcs between phases. In other tests a spark gap under oil was placed between the connection to the primary winding and ground. The spark gap was preadjusted to sparkover at a given voltage [15].

In addition to standard tanks which were modified for instrumentation, tests were also done with several transformers which had either failed during service or which the researchers caused to fail. In some of these transformers the voltage was interrupted before the fault became to violent, and the transformers were taken out of service. By energizing the transformers again under controlled conditions in the laboratory, these tests would help to give a better understanding of what occurs while a transformer is in the process of failing [10], [15].

Tests were also done by deliberately overloading of three new transformers to get them to fail in the laboratory. Each of these failed by developing a high impedance fault in the windings which took considerable time to develop into a high current fault. Then these units behaved quite similarly to the field failures [10].

3.3.2 Results from the tests

Critical factors affecting the risk of violent failures:

From the test results the researchers tried to find limits for the energy input which the transformer could withstand without getting a tank rupture. But results from tests in different test laboratories showed that it was almost impossible to determine this limit. It depends on such factors as the size of the transformer, the design of the transformer, and where the arc is established in the faulty transformer [17], [21], [30].

Tests on pad mounted transformers showed that because of the size, shape, and construction, the pad mounted tank is capable of absorbing many times more energy than the overhead tank. The walls of the pad mounted tank have large flat areas which may bulge or deform to dissipate energy, while the cylindrical tank can deform very little during the fault [31]. The welded construction also appears to add considerable strength. But tests also showed that this added strength may also have the effect that when the units ruptures it does so with added violence [21].

Arcs drawn in oil in a transformer cause almost immediate decomposition of the surrounding oil into combustible and noncondensable gases and propagation of a shock wave through the remaining body of the oil. If the arc power and energy is sufficiently large, disruption of the transformers enclosure will occur. Because of the interrelated factors affecting this behavior, it is virtually impossible to predict solely in terms of the power system conditions when a failure will be disruptive. The distribution system characteristics, the electrical characteristics of the fault, and the physical characteristics of the transformer all interact to produce the final result. A wide range of fault power and energy was observed even for the same levels of available fault current, thus showing the difficulty in defining a typical fault [21].

In [30] it is found that the total energy generated during a multiple loop interrupting period did not appear to be a major factor as related to cover failure. A time-energy relationship appears to exist such that the energy generated during the first half cycle of arcing may be the controlling factor. This is in agreement with the full scale tests described in [33] and in chapter 8. On the other hand the arcing duration was found to be a critical factor in [17].

In [11] it was found that cover failures did not depend entirely on the peak pressure magnitude. The shape of the waveform was also found to be significant. A high rate of rise of pressure is detrimental, especially with venting covers which have a finite flow rate capability and response time. But brief pressure peaks greatly exceeding the static pressure limit may be withstood.

In tests described in [10] it was found that faults contained within the winding produced less pressure in the transformer than either an open arc or an expulsion fuse did, even for similar arc energies. Calculations indicated that the lower pressure produced by the arc in the winding might be due to the cooling of the gas by the layers of windings and insulation through which the gas passes. Another source of energy loss when the arc is within the winding is the considerable flow impedance which the complex winding passages offer to the high velocity flow of oil displaced by the arc bubble. In [10] it was concluded that winding faults are less severe than one inch long arcs drawn directly in oil.

The arc energy depends directly upon the fault duration and the available current magnitude. The arc voltage is shaped approximately like a square wave with the same polarity as the current, and the magnitude of the arc voltage is independent of the current. The major factor affecting the arc voltage magnitude is the arc length. It has been determined that the voltage gradient is approximately 88 V/cm for open arcs under oil [11].

It seems to be clear that the volume of the gas cushion between the oil and the top of the tank affects the pressure [9]. But there is some disagreement in the literature about the significance of increased volume versus reduced transformer cover area. In [9] it is said that the increased volume

of the gas cushion means more than the increased transformer cover area. In [17] it is said that decreased transformer cover area offsets the increased gas-space compression. That means that the internal pressure reached is greater with a small tank, but the smaller cover area yields about the same force on cover supports as in a larger tank with less internal pressure, and the strength of the cover supports is constant regardless of cover diameter.

The efficiency of pressure relief devices:

It was observed that a self-actuating pressure relief device did not prevent tank rupture due to high current faults. But it will relieve slow-rising pressures due to low-level faults (high impedance faults which eventually can evolve into primary winding faults) and extreme overloading. In this regard, it eliminates the problem of handling or servicing transformers which may have developed high static pressure [9], [10], [17], [21], [30], [32].

Mechanical forces on the transformers:

As mentioned earlier, internal faults in distribution transformers can cause an energy release large enough to blow the cover from the transformer tank or, in some instances, to rupture the tank. But the tests on the American transformers did also show that the transformers were exposed to heavy mechanical shocks. By help of high speed movies from the tests it was observed that the cause of transformer cover failure sometimes appeared to be a moving mass of oil impacting on the cover and causing it to fail. When the cover did not fail the transformer received a severe mechanical shock resulting in the vertical movement of the transformer [30], [32]. The severe mechanical impact imparted to the transformers suggests that damage may occur not only to the lid and clamping mechanism, but also to the coil structure and the transformer mounting bracket [32].

The pressure evolution with different failure modes:

Much research were done, both experimental and theoretical, to find the most frequent causes of tank rupture, especially cover blow-off caused by internal faults in pole-type transformers. The results were that different failure modes occurred depending on where the arc was established inside the transformer tank [9], [10], [11], [17], [31], [32], [34]. The pressure developed in the gas space was the significant variable when an arcing fault occurred.

If an arc should occur in the gas space, the reaction may be unpredictable. If the seal of the unit is broken, sufficient oxygen may be present to permit combustion of the volatile gaseous products of arcing in oil. If no oil is dissociated by the arc, the reaction might be slight.

With a low current or incipient fault of a short arc length, the location of the arc was found not to be significant.

In the cases where the depth down to the arc is great, the oil surface moves upward with almost no distortion, driven by the expanding bubble which forms around the arc. The result is an adiabatic compression of the gas space by the moving of the "oil piston" [10]. This mode was found to be the most probable with a high-current arc [34].

If the power input to a deep-oil arc is high, a so-called depth-charge reaction might occur in which a column of oil is driven up from the surface and strikes the cover [10], [34]. If the depth of the

arc is shallow, a hybrid mode combining the oil piston and the gas space arc modes may occur [34].

If the high current arc is located just below the oil surface, the expanding gas bubble quickly breaks through the surface and mixes with the gas in the gas space. This constitutes a very inefficient process in which the overpressure is produced directly by the addition gas from decomposed oil with no energy transfer by adiabatic compression [10].

Slowly evolving faults:

As mentioned earlier three transformers were deliberately overloaded and failed in the laboratory. The transformers failed by developing a high impedance fault in the windings which took considerable time to develop into a high current fault. Even when high current faults developed in these transformers, a sufficiently high impedance remained in the windings to limit the current to less than the system's available fault current. After repeatedly being energized, high current ground arcs were formed, but they produced only a fraction of the pressure which would be expected based on experience with open arcs and oil expulsion fuses. The results from these tests were compared to the fault development of two faulty transformers returned from the field. The faulty transformers were still sufficiently undamaged so that events could be observed which were probably similar to the original service failures. The tests on these transformers and the tests with the deliberately overloaded new transformers showed that the units behaved quite similarly [10].

The validity of fault simulation with open arcs in oil:

If the results from the tests described in [9] and [10] represent typical transformer failures, then long arcs drawn directly in the oil probably represent an extreme worst case rather than the usual internal fault. There are, however, many types of faults within the transformer which might be well represented by suitably short arcs drawn directly in the oil. Failure of a bushing lead, tracking across the surface of insulation, or a stream of bubbles from the windings resulting in high current flashovers are all representative types of arcs that may occur in service [10]. An 1-inch arc in oil seems far more severe than the typical coil-winding failure [9].

3.4 TESTS WITH GENERATION OF GAS BUBBLES IN DISTRIBUTION TRANSFORMERS

The discussion in this section is based on experiments described in [35] and [36]. There are a number of factors which may lead to the formation of gas bubbles in oil filled apparatus. In transformers such gas bubbles may appear in substantial amounts if oil saturated with gas is subjected to a sudden pressure drop. Significant quantities of gas may also be generated due to the decomposition of the paper insulation during operation at elevated temperature. Under certain conditions the liberation of gas dissolved in oil may be facilitated by the presence of dielectric stress [36].

Limited data has been published on gas bubble formation in the oil-paper insulating system and its functional relationship to a transformer in service. The objectives of the tests described in [37] and [36] was to determine the operating conditions which could result in bubble evolution in a distribution transformer, and to perform a limited investigation of the effect of bubbles on the

breakdown strength of the insulation system. The tests were made on miniature coils and on full scale distribution transformers.

3.4.1 Model coil tests

The model coil construction was a layer winding configuration. The windings consisted of varnish insulated round copper wire, and the coil was wound on a pressboard winding form. The insulation between winding layers consists of a single wrap of thermally upgraded kraft paper.

The model coil was installed with its axis in a vertical position and was supported by a resin-impregnated paper cylinder. After sealing the model coil in the test cell it was subjected to vacuum impregnation with transformer oil.

In a separate coil thermocouples were installed in different places. This coil served as a thermal monitor for calibration tests.

Tests were done with different overload conditions. With moderate ove   .d ($I = 1.55 \cdot I_N$) the hot spot temperature was 140 °C, and gas bubbles were never observed. With severe overload ($I = 2.25 \cdot I_N$) the hot spot temperature became 225 °C. The hot spot temperature which coincided with the first appearance of bubbles ranged from 186 to 210 °C. During the early stages of the severe overload the activity was restricted to single bubbles or small groups of bubbles which were expelled from the top of the winding at infreque..t intervals. With increasing temperature the rate of emission also increased. The emission of gas bubbles ceased almost immediately when the severe overload ceased.

During the aging tests the temperature was about 180 °C. Bursts of 5 to 20 tiny gas bubbles were observed to flow out of the coil infrequently. The bubbles accumulated at the bottom horizontal surface of the coils. The bubbles were held in place by the slightly protruding edges of the layer insulation.

The bubble condition most detrimental to insulation breakdown strength occurred during severe overload while hot spot temperatures exceeded 200 °C and a steady stream of gas bubbles was discharged from the windings. Under these conditions the insulation strength between layers decreased to almost half of its value at rated load, but recovered to the previous level soon after the overload was removed [35].

3.4.2 Bubble observations on full scale distribution transformers

The test sample used for bubble observations was a 37.5 kVA 7200/0.24(0.12) kV pole type distribution transformer. It had thermocouples embedded in the hot spot zone of the winding, in the top oil, on the tank cover and on the tank wall. The authors thought that cooling of the loaded transformer by means of a simulated rain test was the condition most likely to initiate bubble evolution. The transformer was loaded by shortening the low voltage terminals together with connecting the high voltage terminals to a variable auto-transformer. This short circuit connection was used in preference to excitation at rated voltage to eliminate any possible effect due to voltage

stress. The observations made during the tests can be summarized as follows [35]:

- A high rate of precipitation was usually necessary to induce bubble activity.
- Bubble emission caused by rain cooling was observed over a range of transformer operating conditions, mostly at or above rated load. The intensity of bubble emission during rainfall was very dependent on load current.
- Bubbles ranged in size from barely visible to about 1/4 inch in diameter. They usually appeared at irregular intervals in bursts of 1 to 10 bubbles from between layers of the high voltage and the low voltage winding, and from the insulation between core and coil.
- All bubbles appeared to originate from within the coil and its insulation.
- Experiments indicated that the primary source of bubbles in an oil-paper insulating system during the early stages of an overload is the moisture that is absorbed within the paper at the time when the overload starts. In the sealed system the moisture content will increase with time as a result of thermal degradation of the paper. Then the moisture content will change as the load varies, since the resulting changes in system temperatures will lead to redistribution of moisture between the oil, the paper and the overhead gas space. Transformers may develop bubbles fairly soon after being placed in service, and they may remain susceptible to bubbling during the remaining life.

3.5 MODEL TESTS WITH SHORT CIRCUITS BETWEEN TURNS

This section is based on tests with a model transformer described in [2]. The purpose of the tests was to observe the evolution of a winding fault.

3.5.1 Test conditions

The model winding was wound on a typical insulating former and consisted of two layers of four turns per layer. The end of each turn was brought to a terminal board so that it could be effectively incorporated with a 400 kVA dry type transformer. The model winding was in principle constructed as shown in Figure 3.2. The voltage ratio for the dry type transformer was 20/0.4 kV and the connection group was Dyn5. Each test winding consisted of two sections. One section had a conductor with a high diameter (Ø=13 mm Cu) surrounded a limb of the test transformer. This section provided the induced turn voltage on the test winding. The other section had a conductor cross section comparable to that of the real transformer winding and was connected in series to the section with bigger diameter. It represented the real resistance of one turn and was also an equivalent of its thermal withstand. All additional test winding sections (8 turns) were connected in series with the small cross-section parts and connected in series with the winding of the 400 kVA transformer. The model coil was immersed in an oil-filled vessel.

3.5.2 Results from the tests

In the first test, all 8 turns were short-circuited by removing the insulation from the first and the

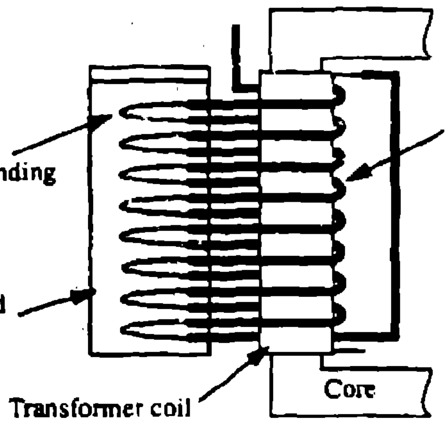


Figure 3.2 Construction of the external model winding.

eight turn representing an insulation fault between two layers. The current in the short-circuited coil was measured to be about 1 kA. The power was switched off after 5.7 sec. Most of the insulation on the model coil had melted and nearly all turns were electrically connected. Enormous amounts of gas was said to be produced during the whole period of the test [2].

The second test was performed on a new model coil, arranged as before. In this test two neighbouring turns in the middle of the inner layer was short-circuited. The power was switched off after 26 sec. Again the current in the short-circuited turn was measured to be about 1 kA. The heating produced further damage to the wire insulation leading to electrical contact between the two layers. The high current caused the wires to melt. It is said that the arc was extinguished by the oil. Also in this test there was a very large production of gas. It is concluded that this test confirms that there is a realistic probability that an arc produced by the melting of the winding wire in the event of a fault will be extinguished due to the excellent arc extinguishing and cooling properties of the transformer oil [2].

From these tests the authors learned that a winding failure in an oil filled transformer will either expand rapidly to neighbouring turns with an increasing source side current, or the failure current in the short-circuited turns can be interrupted by the melting-through of a turn conductor.

3.6 FULL SCALE TESTS WITH INTERNAL FAULTS ON EUROPEAN DISTRIBUTION TRANSFORMERS

In the period 1984-1991 tests with different kind of internal faults in distribution transformer have been carried out in France [38] and in Germany [39], [40]. Because these tests are very close to the tests done in this work, the tests and the results from [38], [39] and [40] will be briefly described in this section.

In 1988, tests on eight 100 kVA distribution transformers with rated primary voltage of 10 and 20 kV were carried out. Some of the results are presented in [39] and [40]. In this section these tests will be called "Tests in 1988 described in [39]".

As many as 23 tests were done with internal faults in 250-630 kVA distribution transformers in 1991, and some of the results are presented in [39]. To avoid the fault currents to cease, most of the transformers were loaded with 70-100% of the rated power during the tests. The transformers were not protected during the tests, because the researchers wanted to study the complete fault development. In this section these tests will be called "Tests from 1991 described in [39]".

The presentation of results from the internal tests is divided in three parts:

- insulation fault between MV-phases
- insulation fault between MV-turns
- insulation fault between LV-turns

3.6.1 Insulation fault between MV-phases

Tests described by Christian et.al. [38]:

A spark gap was applied inside the transformer tank in order to create an arc between two phases, downstream from the MV terminals. A series of tests showed the capacity of the transformer envelopes to withstand the stresses resulting from internal arcs of low current. An explosion time/short-circuit intensity curve was determined for this kind of fault for a 100 kVA distribution transformer. As one example, an internal arc initiated by a 10 mm spark gap, current 6 kA, time 200 ms, led to the injection of arc energy of about one megajoule. The pressure rise was then about one bar. In [38] it is said that these values can be withstood by modern transformer envelopes.

Tests in 1988 described by Hampel et.al. [39]:

No noticeable fault development was observed when the short circuit was established between two MV-phases just under the transformer cover when the transformer was protected with high voltage, current limiting fuses[1].

With an identical transformer and type of fault as above, but without fuses in series, the bushings were ruptured, and the transformer tank cracked after 15 ms and the oil burned violent.

3.6.2 Insulation fault between MV-turns

Tests described by Christian et.al. [38]:

This type of fault is in [38] considered to be the one of the most common failures. A hole was

1 In German called "Hochspannungs-Hochleistungs-Sicherungen".

drilled in one of the MV windings, into which a small metal rod was inserted. On two occasions tests with faults between medium voltage turns were carried out.

Test 1: The fault slowly (~1 min.) developed into a phase-earth fault which was quickly remedied by the upstream protection system. On reclosing the phase concerned was isolated and no restrike was observed. The overpressure within the envelope was 0.5 bar at the end of the test.

Test 2: The behavior observed in test 1 was not reproduced. The fault remained unchanged in this test. But on removal of the transformer from the envelope, a slight gaseous release was observed.

In these two tests, the faults between MV-turns gave no sudden degeneration.

Tests in 1988 described by Hampel et.al. [39]:

Short circuit between MV-turns developed in different ways depending on how large part of the MW winding was short-circuited:

- When only a few turns were short-circuited, the fault did not always lead to complete short circuit, sometimes the fault disappeared by itself.
- When a large part of the coil was short-circuited, the line currents reached values several many times the rated primary current of the transformer. Suddenly the current increased to the short circuit current. The bushings exploded, and in one test the transformer tank cracked, and the oil burned violent.

Tests in 1991 described by Hampel et.al. [39]:

Table 3.1 gives a survey of the transformers tested with insulation faults between MV-turns.

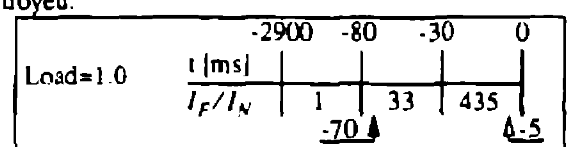
	Test 2	Test 3	Test 4	Test 5	Test 8	Test 10	Test 11
Rated voltage [kV]	10	6	6	20	11	20	20
Rated power [kVA]	400	500	315	500	630	250	630
Z_{sc} [%]	3.9	5.85	3.6	6.0	6.0	4.3	3.9
Connection group	Dy5	Dy5	Dy5	Dz6	Dy11	Dy5	Dy5
Production year	1990	1958	1955	1962	1989	1986	1971
Tank type (1)	H	C	C	C	H	H	C
(1) H = Hermetically sealed, C = Conservator type							

Table 3.1 Transformers tested with insulation faults between MV-turns in 1991 described in [39].

	Test 2	Test 3	Test 4	Test 5	Test 8	Test 10	Test 11
MV-winding	Layer	Layer	10+2/2 Cross-over	18+2/2 Cross-over	6 Cross-over	Layer	18 Cross-over
LV-winding	Sheet	Spiral	Spiral	Spiral	Spiral	Spiral	Spiral
(1) H = Hermetically sealed, C = Conservator type							

Table 3.1 Transformers tested with insulation faults between MV-turns in 1991 described in [39].

The type of MV-insulation failure and the results from the tests described in [39] is briefly described in Table 3.2.

Test no.	Type of insulation fault between MV-turns	Fault development
2	Short circuit between layers through a resistor in the MV-winding on limb B.	Transitory arcs were established near the MV-bushings. The tank cracked, followed by an oil leakage. The MV-winding on limb B was destroyed by compressive stresses. The MV-winding on limb A was destroyed near the tappings. The links between the bushings and the MV-windings were destroyed.  At t=0 the tank cracked, and the pressure was 3.6 bar[1].

Phase A and C are the outer phases, and phase B is the centre phase.
(1): Expressed in [39] as "Druckmaximum" or pressure when "Kessel platzt".
Filled arrow: Implemented by the author of this thesis. Expected total clearing time for a correct dimensioned CL fuse type CEF manufactured by ABB
Open arrow: Implemented by the author of this thesis. Expected total clearing time for a right dimensioned inverse overcurrent time relay used by ABB together with a vacuum circuit breaker. (Minimum tripping current for the relay is set to be $2 \times I_N$ for the transformer.

Table 3.2 Type of MV-insulation failures and the results from the tests described in [39].

Test no.	Type of insulation fault between MV-turns	Fault development
3	About 50% of the turns used in the tap selector for the MV-winding on limb B was short-circuited by a screw.	A crack was heard just after the transformer was energized. Some oil came out from the seal of one LV-bushing and from the cap on the conservator. Load=0.7 t [ms]: -70, -60, 0 I_F/I_N: 1, 187 -50 (filled arrow), +40 (open arrow) The maximum pressure was 2.8 bar.
4	About 8% of the turns in the upper part of the MV-winding on limb B was short-circuited by a screw.	Smoke came out of the conservator during the test, and loud noise was heard. The two uppermost MV-coils on limb B were damaged. Load=0.7 t [min]: -17, 0 I_F/I_N: 1 The transformer was disconnected at t=0.
5	About 5% of the turns in the middle part of the MV-winding on limb B was short-circuited by a screw.	Smoke came out of the conservator and load noise was heard during the test. A crack was heard when the full short circuit current was established. The tank got a slight deformation ("pregnant"), and three small holes were observed. The middle and the upper part of the MV-winding on limb B was damaged. Two links between the bushings and the MV-windings were teared off. Load=0.7 t [ms]: -50000, -107, -97, -85, -40, 0 I_F/I_N: 0.7, 1.5, 625, 0, 625, 0 -97 (filled arrow), -10 (open arrow) The maximum pressure was 1.7 bar.

Phase A and C are the outer phases, and phase B is the centre phase.
(1): Expressed in [39] as "Druckmaximum" or pressure when "Kessel platzt".
Filled arrow: Implemented by the author of this thesis. Expected total clearing time for a correct dimensioned CL fuse type CEF manufactured by ABB
Open arrow: Implemented by the author of this thesis. Expected total clearing time for a right dimensioned inverse overcurrent time relay used by ABB together with a vacuum circuit breaker. (Minimum tripping current for the relay is set to be $2 \times I_N$ for the transformer.

Table 3.2 Type of MV-insulation failures and the results from the tests described in [39].

Test no.	Type of insulation fault between MV-turns	Fault development
8	About 20% of the turns in the upper part of the MV-winding on limb B was short-circuited by a screw.	Just after the transformer was energized, loud growling was heard. After 10 sec. stable load conditions were reached. The pressure relief device operated 4 sec. after the transformer was energized. Gas came out of the bleeder valve for many minutes. Load=1.0; t [s]: -420, -410, 0; I_F/I_N: 2.3, 1 The transformer was disconnected at t=0.
10	4 of 13 layers in the MV-winding on limb A were short-circuited by a screw.	The tank was inflated, and one corner in the upper part of the tank cracked. All the layers in the MV-winding on limb A were destroyed. Load=0.7; t [ms]: -300, -12, 0; I_F/I_N: 28, 1330; -283▲ △-225 At t=0 the tank cracked, and the pressure was 2.8 bar.
11	Two crossover coils in the middle part of the HV-winding on limb B were short-circuited by a screw.	The transformer exploded, and large amounts of burning oil splashed out from the destroyed transformer tank. Two of the MV-bushings were destroyed. The MV-windings in limb A and B were badly damaged. The LV-windings were not destroyed. Load=0.0; t [s]: -33000, -840, -570, -200, -80, 0; I_F/I_N: 2, 3, 8, 11, 467; △-32650 ▲-540 At t=0 the tank cracked, and the pressure was 4.8 bar.

Phase A and C are the outer phases, and phase B is the centre phase.
(1): Expressed in [39] as "Druckmaximum" or pressure when "Kessel platzt".
Filled arrow: Implemented by the author of this thesis. Expected total clearing time for a correct dimensioned CL fuse type CEF manufactured by ABB
Open arrow: Implemented by the author of this thesis. Expected total clearing time for a right dimensioned inverse overcurrent time relay used by ABB together with a vacuum circuit breaker. (Minimum tripping current for the relay is set to be $2 \times I_N$ for the transformer.

Table 3.2 Type of MV-insulation failures and the results from the tests described in [39].

3.6.3 Insulation fault between LV-turns

Tests described by Christian et.al. [38]:

There are two main origins for the low voltage faults:

- the LV network in the case of the lack or incorrect adaptation of the LV protection downstream from the transformer (called external origin)
- fault between LV-turns (called internal origin)

The authors of [38] considered that these two origins had equivalent consequences. The LV faults were for simplicity caused by creating a low voltage short circuit outside the transformer.

All the LV faults caused fairly comparable effects. A current of about $I_F \approx 20 \times I_N$ appeared after the transformer was energized. After about 30 sec., the current rose, and during a few periods it reached a value of about $60 \times I_N$. It is believed that this increase in the current was caused by short-circuiting of turns. The current continues to increase until it reached the current corresponding to the short circuit power in the point where the transformer was installed.

For high short circuit power (150 MVA) the transformers exploded. Parts were projected more than 3 meters away, and flames were observed more than two meters from the envelope. In some of the tests the maximum overpressure was measured to be 4 bars.

Tests in 1988 described by Hampel et.al. [39]:

Short circuit between turns in the LV winding led to the same type of fault development as mentioned above. The fault developed faster than in the tests with short circuits in the MV winding.

Tests in 1991 described by Hampel et.al. [39]:

Table 3.1 gives a survey of the transformers that were tested with insulation faults between LV-turns.

	Test 1	Test 6
Rated voltage [kV]	20	20
Rated power [kVA]	400	500
Z_{sc} [%]	4.0	6.0
Connection group	Dy5	Dz6
Manufacturing year	1990	1961
Tank type [1]	C	C
[1] C = Conservator type		

Table 3.3 Transformers tested with insulation faults between LV-turns in 1991 described in [39].

	Test 1	Test 6
MV-winding	Layer	22+2/2 Cross-over
LV-winding	Sheet	Spiral
(1) C = Conservator type		

Table 3.3 Transformers tested with insulation faults between LV-turns in 1991 described in [39].

The type of LV-insulation failure and the results from the tests described in [39] is briefly described in Table 3.2.

Test no.	Type of insulation fault between LV-turns	Fault development
1	Layers in the LV-winding on limb A were short-circuited by a thick screw.	The transformer tank was heavily deformed and cracked. The destruction of the windings started in the winding on limb A, and after that sparkovers occurred in the tap selector. This led to a destruction of the tappings for the MV-windings on limb B and C. Load=0.7 t [ms]: -2980 -1800 -1100 -300 -33 0 I_F/I_N: 0.7 | 7 | 17 | 30 | 870 -960 -800 At t=0 the tank cracked, and the pressure was 5.6 bar.

Phase A and C is the outer phases, and phase B is the centre phase.
Filled arrow: Implemented by the author of this thesis. Expected minimum melting time for a right dimensioned CL fuse type CEF manufactured by ABB
Open arrow: Implemented by the author of this thesis. Expected total clearing time for a right dimensioned inverse overcurrent time relay used by ABB together with a vacuum circuit breaker. (Minimum tripping current for the relay is set to be $2 \times I_N$ for the transformer.

Table 3.4 Type of LV-insulation failures and the results from the tests described in [39].

<table>
<tr><th>Test no.</th><th>Type of insulation fault between LV-turns</th><th>Fault development</th></tr>
<tr><td>6</td><td>The middle part of the LV-windings on limb A and B were short-circuited to each other.</td><td>Arcs were established on the links just under the bushings. One MV-bushing ruptured, and oil was burning through the hole. Oil started to leak out from the tank. Some turns in the MV-winding were broken, and the uppermost coil on limb B was crushed. Much copper from the LV-windings was observed on the bottom of the tank after the test.
Load=0.0
t (ms): -12000 | -100 | -20 | 0
I_F/I_N: 12 | 590 | 0
-11820 -11450
At t=0 the tank cracked, and the pressure was 2.1 bar.</td></tr>
<tr><td colspan="3">Phase A and C is the outer phases, and phase B is the centre phase.
Filled arrow: Implemented by the author of this thesis. Expected minimum melting time for a right dimensioned CL fuse type CEF manufactured by ABB
Open arrow: Implemented by the author of this thesis. Expected total clearing time for a right dimensioned inverse overcurrent time relay used by ABB together with a vacuum circuit breaker. (Minimum tripping current for the relay is set to be $2 \times I_N$ for the transformer.</td></tr>
</table>

Table 3.4 Type of LV-insulation failures and the results from the tests described in [39].

3.6.4 Main results from the tests

During dissection of the exploded transformers, it was seen that in some cases the links had not withstood the overcurrent resulting from the transformer's internal fault [38], [39]. The melting of the links may be serious enough to give an arc in the transformer envelope with sufficient energy to cause rupture or explosion of the transformer tank.

The tests described in [39] showed that when the fault developed to be a full short circuit, this happened extremely fast. In [39] it is said that if this current is not interrupted within 20 ms, the transformer tank will crack. During the tests with insulation failures in the MV-windings described in [38], the faults gave no sudden degeneration. But in the tests described in [38], the authors say that they were unable to wait long enough to evaluate how the fault would have developed in the long run.

The results from the tests described in [38] showed that an insulation fault between LV-turns gave rise to the most violent external manifestation. From the tests presented in [39] it was found that an insulation fault between LV-turns developed faster than in the tests with short circuits in the MV-winding.

From the tests described in [39] it is seen that great variations in how fast the MV insulation failure develops further are observed. In one case a short circuit was established only 70 ms after the transformer was energized, and in another case nothing special happened during 17 minutes. It is also clear that the speed of evolution depends on the winding construction and the site of the initial breakdown. It seems as a winding fault in a transformer with layer windings evolves more quickly than a winding fault in a transformer with crossover coils. The reason for this may be that a winding fault in a layer winding quickly involves a substantial part of the whole winding.

From test no. 4 and 11 in Table 3.2, a kind of equilibrium occurred with the heat produced and the heat conducted away. The faults persisted for a long time before they developed further (in test no.4 the transformer was disconnected after 17 min.).

The discussion about how the transformers could have been protected will be considered in section 9.6.3.

3.7 CONCLUSIONS

The results from the tests with internal arcs in small distribution transformers done in the sixties and the seventies showed that it was almost impossible to determine the limits for the energy input which the transformers could withstand without getting a tank rupture. Other main results from this research were:

- Faults contained within the coil's windings produced less pressure in the transformer than open arc faults did, even for similar arc energies. This is due to the cooling of the gas by layers of windings and insulation through which the gas passes.
- Winding faults are less severe than one inch arcs drawn directly in oil.
- The major factor affecting the arc voltage magnitude is the arc length. The voltage gradient for open arcs under oil was found to be approximately 88 V/cm.
- Self-actuating pressure relief devices do not prevent tank rupture due to high-level faults.
- Long arcs drawn directly in the oil probably represent a worst case rather than the usual internal fault.

Other tests have shown that there are great variations in how fast the MV insulation failure develops further. The evolution behavior depends on the winding construction and the site of the initial breakdown. Tests have also shown that a kind of equilibrium may occur between the heat generated and the heat being conducted away.

Tests with severe overload of transformers showed that gas bubbles appear to originate from within the coil and insulation when the conductor temperature exceed about 145 °C. Under conditions with bubble formation, the insulation strength between layers decreased considerably.

4 CALCULATION MODELS FOR CURRENTS DUE TO FAULTS BETWEEN TURNS IN TRANSFORMER WINDINGS

4.1 SUMMARY

When an insulation failure occurs between turns of a winding in a three phase transformer, calculations of currents and voltages by symmetrical components becomes very complex. Among other factors, the fault currents depend on the number of turns short-circuited, their position in the winding and the type and connection of the transformer.

Based on a report written by Coleman [5], equations which describe the relations between currents and applied voltages for single- and three-phase transformers are developed, with a given fraction of the primary winding short circuited. The equations evolved are presumably of limited practical use. To follow the development of the equations may, however, help to increase the knowledge and understanding of what is happening electrically during a short circuit between turns in a transformer.

It is important to know the influence of partial winding short circuits on the line currents, because of the possibility of detecting these faults at an early stage. The present work tries to summarize results reported in the literature and to link this to results obtained in this work.

The inductances used in the equations can not be calculated analytically. They can be calculated numerically by help of a magnetic field calculation program, but such calculations is outside the scope of this work.

One of the assumptions used in the development of the equations in the literature is to neglect the non-linearity of the transformer core. During the present work measurements in the laboratory have shown that this assumption entails major errors when larger parts of a coil are short-circuited in a star/star or delta/star connected distribution transformer.

When the transformer is star/star connected, the voltages across the two other phases are increasing, and because of the core saturation the magnetizing currents are heavily increased, resulting in increased line currents.

When the transformer is delta/star connected, and when a fraction of one primary winding is short-circuited, the damaged limb behaves as a single-phase transformer with the line voltage across its terminals with the other limbs unaffected. Then the voltage per turn is increasing when the number of short-circuited turns is increasing, giving an increased magnetizing current.

Much of the theory that is to be dealt with in this chapter is described in [5] and [22].

4.2 ASSUMPTIONS, DEFINITIONS AND GENERAL PRINCIPLES

In all the calculations it is assumed that only the primary windings are energized and that the transformer is off-load.

The supply system is supposed to be so strong that the terminal voltages are unaffected by the fault currents drawn. When nothing mentioned, the effects of winding resistance are ignored.

When there is a fault between turns in a three-phase transformer, the transformer becomes asymmetrical, and calculations by help of symmetrical components are very complicated. Coleman [5] has developed a direct method of analysis.

The accurate formulae obtained sometimes look very complex. To overcome this, Coleman [5] makes certain approximations that present the results in terms of "generalized zero-phase sequence reactances".

Currents, voltages and fluxes are assumed sinusoidal, and r.m.s. values are used throughout.

The basic assumptions for the following calculations are:

Assumption 1: The flux induced by a current-carrying coil has two components;

i) it's path is entirely in the iron circuit. It is called the "core flux".

ii) it's path is entirely in air, or partly in air and partly in iron. It is called the "leakage flux".

Assumption 2: The core flux induced in a limb by a winding returns equally between the remaining limbs.

Assumption 3: The leakage flux induced by any coil links in part with every other coil of the transformer.

The "mutual leakage reactance", X_{mn}, between coils m and n, is the ratio of the e.m.f. induced in coil m by unit current in coil n, when the leakage between the coils is solely by leakage flux.

The "mutual leakage inductance", L_{mn}, is given by $X_{mn}=\omega L_{mn}$, and as usual $L_{mn}=L_{nm}$.

The "self leakage inductance", L_{mm}, is similarly defined. (See Figure 4.2 and equations (4.7) and (4.10)).

Assumption 4: The mutual leakage inductance between coils on different limbs is ignored.

Assumption 5: Non-linearity, hysteresis, eddy-current losses etc. are neglected. It follows that the core flux induced by a coil is proportional to the ampere turns of that coil.

Assumption 6: As a first approximation the total core flux in any limb calculated by help of assumption 2 and 4 is zero. This corresponds to the theorem of m.m.f. balance between load currents. (m.m.f. = magnetomotive force in magnetic-circuit terminology).

Superimposed on this balanced system is a "magnetizing flux" in the iron circuit, concerned solely with inducing the requisite back e.m.f's (electromotive force) in the coils. This is in turn induced by "magnetizing currents" in the coils of the transformer. The magnetizing currents are negligible compared to the load currents.

It can be useful to divide the core flux into circulating fluxes. Thus in the three-phase case let Φ_{AB} stand for the core flux circulating between limbs A and B, with similar definitions for Φ_{BC} and Φ_{CA}. Let the convention be that Φ_{AB}, Φ_{BC} and Φ_{CA} are positive in a clockwise direction where A, B and C are the limbs from left to right. See Figure 4.1.

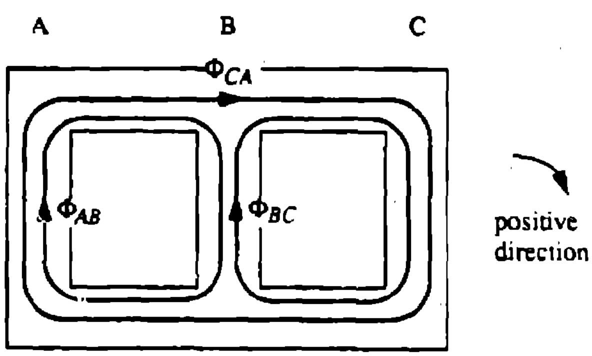


Figure 4.1 Definition of positive core fluxes.

Total core flux in limb A: $(\Phi_{AB} + \Phi_{CA})$
Total core flux in limb B: $(-\Phi_{AB} + \Phi_{BC})$
Total core flux in limb C: $(-\Phi_{BC} - \Phi_{CA})$

If there is an undamaged delta winding on the frame, with N turns in each coil, then the e.m.f.'s induced in them will be $kN(\Phi_{AB} + \Phi_{CA})$, etc., where k is a proportionality factor. By addition, the total e.m.f. induced in the delta winding is zero whatever the core flux distribution may be.

4.2.1 Definitions of L_{11}, L_{22} and L_{12}

The basis for the definitions is shown in Figure 4.2.

N_P and N_S are defined in Figure 4.3 on page 43. The relationship $\Phi = \mathcal{P}NI$ is given, where $\mathcal{P}$ is the permeance of the space occupied by the flux Φ, [41]. Referring to Figure 4.2 the fluxes can be related to the coil currents as follows:

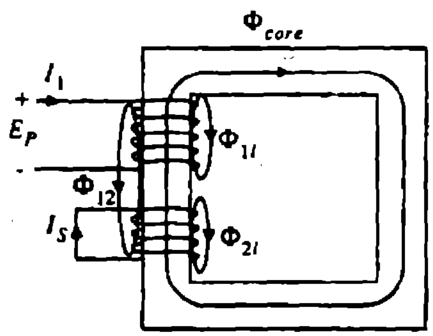


Figure 4.2 Definitions of the fluxes used to deduce the inductances used in this chapter.

$$\Phi_{1l} = \mathcal{P}_{1l}(N_P - N_S)\, I_1 \tag{4.1}$$

$$\Phi_{2l} = \mathcal{P}_{2l} N_S I_S \tag{4.2}$$

$$\Phi_{12} = \mathcal{P}_{12}(N_P - N_S)\, I_1 + \mathcal{P}_{12} N_S I_S \tag{4.3}$$

$$\Phi_{core} = \mathcal{P}_{core}(N_P - N_S)\, I_1 + \mathcal{P}_{core} N_S I_S \tag{4.4}$$

The total flux linking coil 1 is denoted by

$$\Phi_1 = \Phi_{1l} + \Phi_{12} + \Phi_{core} \tag{4.5}$$

The flux linkage λ_1 is given as

$$\lambda_1 = (N_P - N_S)\,\Phi_1 \tag{4.6}$$

$$\lambda_1 = \overbrace{(\mathcal{P}_{1l}(N_P - N_S)^2 + \mathcal{P}_{12}(N_P - N_S)^2)}^{L_{11}}\, I_1 + \overbrace{(\mathcal{P}_{12}(N_P - N_S) N_S)}^{L_{12}}\, I_S$$
$$+ \underbrace{\mathcal{P}_{core}(N_P - N_S)^2 I_1 + \mathcal{P}_{core}(N_P - N_S) N_S I_S}_{\text{The part of the flux linkage for coil 1, whose path is entirely in the iron circuit.}} \tag{4.7}$$

The total flux linking coil 2 is denoted by

$$\Phi_2 = \Phi_{2l} + \Phi_{12} + \Phi_{core} \tag{4.8}$$

The flux linkage λ_2 is given as

$$\lambda_2 = N_S \Phi_2 \tag{4.9}$$

$$\lambda_2 = \overbrace{(\mathcal{P}_{2l}N_S^2 + \mathcal{P}_{12}N_S^2)}^{L_{22}} I_S + \overbrace{(\mathcal{P}_{12}(N_P - N_S)N_S)}^{L_{12}} I_1$$

$$+ \underbrace{\mathcal{P}_{core}(N_P - N_S)N_S I_1 + \mathcal{P}_{core}N_S^2 I_S}_{\text{The part of the flux linkage for coil 2, whose path is entirely in the iron circuit.}} \tag{4.10}$$

The inductances L_{11}, L_{22} and L_{12} can theoretically be calculated numerically by help of a magnetically field calculation program. In principle the inductances are calculated as follows [42]:

Let a current I pass through coil 1. Calculate the field energy $W_{magn,1}$ outside the core. Then the inductance L_{11} can be derived from the field energy as

$$L_{11} = \frac{2W_{magn,1}}{I_1^2} \tag{4.11}$$

Let then a current I_2 pass through coil 2. Calculate the field energy $W_{magn,2}$ outside the core. Then the inductance L_{22} can be derived from the field energy as

$$L_{22} = \frac{2W_{magn,2}}{I_2^2} \tag{4.12}$$

Let then a current I_1 pass through coil 1 and a current I_2 pass through coil 2. Calculate the field energy $W_{magn,12}$ outside the core. Then the mutual inductance L_{12} can be derived as

$$L_{12} = \frac{W_{magn,12} - \frac{1}{2}L_{11}I_1^2 - \frac{1}{2}L_{22}I_2^2}{I_1 I_2} \tag{4.13}$$

It can be a numerical problem to calculate $W_{magn,1}$ and $W_{magn,2}$ since most of the field energy is stored in the core. It is easier to calculate $W_{magn,12}$, because most of the field energy is stored outside the core when there is m.m.f. balance between the load currents.

4.3 EXPRESSIONS FOR THE BASIC REACTANCES IN TERMS OF LEAKAGE INDUCTANCES

Figure 4.3 represents a single-phase transformer wound on one limb. For convenience the currents are represented as flowing from the top to the bottom of the coils. N_P is the number of turns in the undamaged primary coil, N_S the number short-circuited, and $(N_P - N_S)$ the number

of turns in the part of the winding sandwiching the short-circuited part.

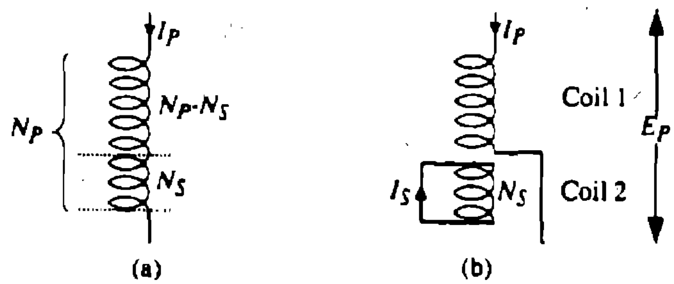


Figure 4.3 Primary coil before (a) and after (b) the short circuit between turns is applied.

4.3.1 The reactance X_l:

Referring to Figure 4.3(b), induced e.m.f's are considered positive if induced by currents flowing from top to bottom of the coils. The e.m.f.'s induced in coils 1 and 2 by leakage coupling are given by

$$\frac{E_1'}{j\omega} = I_P L_{11} + I_S L_{12} \tag{4.14}$$

$$\frac{E_2'}{j\omega} = I_P L_{21} + I_S L_{22} \tag{4.15}$$

By using the approximation that there is m.m.f. balance it is found that;

$$I_P(N_P - N_S) + I_S N_S = 0 \tag{4.16}$$

The total e.m.f. induced in coil 2 must be zero because it is short-circuited. This is equivalent to saying that sufficient magnetizing core flux must exist to induce an e.m.f. of $-E_2'$ in N_S turns of coil 2. The expression for the core flux is given in equation (4.4) on page 41. Since this flux is linked with the remaining turns in coil 1, it will induce them with a total e.m.f. of $-\frac{N_P - N_S}{N_S} E_2'$.

The applied e.m.f., E_P, is therefore given by the sum of this component and E_1'.

$$\frac{1}{j\omega} E_P = I_P L_{11} + I_S L_{12} - \frac{N_P - N_S}{N_S} \left[I_P L_{12} + I_S L_{22} \right] \tag{4.17}$$

Writing $n = \frac{N_p - N_S}{N_S}$ and combining equation (4.16) and (4.17) it is found

$$\boxed{\frac{X_l}{\omega} = L_l = \frac{E_P}{j\omega I_P} = L_{11} + n^2 L_{22} - 2nL_{12}} \tag{4.18}$$

A brief interpretation of X_l with regard to permeances and the number of turns in coil 1 and 2:

From equation (4.7) and (4.10) it is seen that

$$L_{11} = (\mathcal{P}_{1l} + \mathcal{P}_{12})\,(N_P - N_S)^2 \tag{4.19}$$

$$L_{22} = (\mathcal{P}_{2l} + \mathcal{P}_{12})\,N_S^2 \tag{4.20}$$

$$L_{12} = \mathcal{P}_{12}\,(N_P - N_S)\,N_S \tag{4.21}$$

If equation (4.19), (4.20) and (4.21) is combined with (4.18), it is found that

$$\frac{X_l}{\omega} = L_l = \frac{E_P}{j\omega I_P} = (\mathcal{P}_{1l} + \mathcal{P}_{2l})\,(N_P - N_S)^2 \tag{4.22}$$

It can be seen that both $\mathcal{P}_{l1}$ and $\mathcal{P}_{l2}$ are decreasing when the number of short-circuited turns, N_S is increasing.

4.3.2 The reactance X_{0P}:

Figure 4.4 represents a n-phase star winding wound on n limbs, which is connected to the supply so that the same current and voltage apply to each coil.

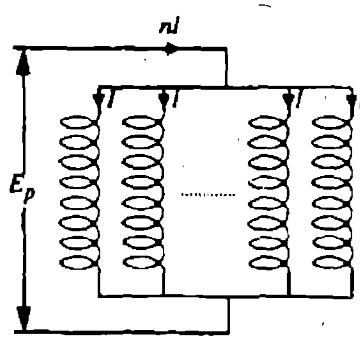


Figure 4.4 A n-phase star winding wound on n limbs.

When E_P is the voltage across the system and I the current in each coil, the "zero-phase sequence reactance" of each coil is defined by

$$X_{0P} = \frac{E_P}{jI} \tag{4.23}$$

From assumption 2 in section4.2 it is seen that the resultant core flux in any limb is zero. As far as the mutual leakage inductance between coils on different limbs is ignored, X_{0P} is the self-leakage reactance of the undamaged coil on one limb. X_{0P} is then a property only of the coil and its position relative to the magnetic circuit. From Figure 4.3(a) and (b) it is found that

$$\boxed{\frac{X_{0P}}{\omega} = L_{PP} = \frac{E_P}{j\omega I} = L_{11} + L_{22} + 2L_{12}} \tag{4.24}$$

4.3.3 The reactance X_{0D}:

Figure 4.5 represents a n-phase star winding where a delta winding has been added to the transformer.

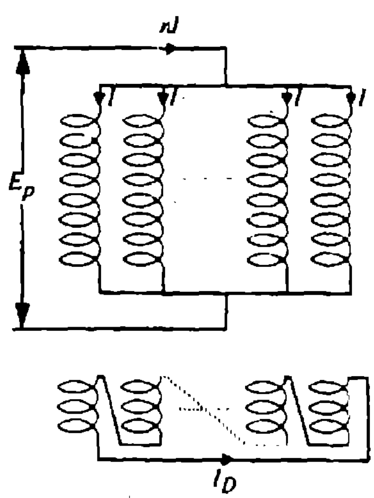


Figure 4.5 A n-phase star winding where a delta winding has been added to the transformer.

The "zero-phase sequence reactance" is defined as

$$X_{0D} = \frac{E_P}{jI} \tag{4.25}$$

By using the assumption that the mutual leakage inductance between coils on different limbs can be ignored, the e m.f. induced by leakage coupling in each primary coil is given by

$$\frac{E_P'}{j\omega} = IL_{PP} + I_D L_{PD} \tag{4.26}$$

The e.m.f. induced by leakage coupling in each delta coil is given by

$$\frac{E_D'}{j\omega} = IL_{DP} + I_D L_{DD} \tag{4.27}$$

From assumption 2 in section 4.2 it is found that the resultant core flux in each limb is zero, and equations (4.26) and (4.27) give the resultant e.m.f.'s in the various coils. Adding the e.m.f.'s around the delta winding, $3E_D$ must be zero.

$$3j\omega(IL_{DP} + I_D L_{DD}) = 0 \tag{4.28}$$

$$I_D = -I\frac{L_{PD}}{L_{DD}} \tag{4.29}$$

$$E_P = E_P' = j\omega I\left(L_{PP} - \frac{L_{PD}^2}{L_{DD}}\right) \tag{4.30}$$

$$\boxed{\frac{X_{0D}}{\omega} = \frac{E_P}{j\omega I} = \left(L_{PP} - \frac{L_{PD}^2}{L_{DD}}\right)} \tag{4.31}$$

4.4 STAR/STAR-CONNECTED THREE-PHASE TRANSFORMERS

4.4.1 Development of the equations

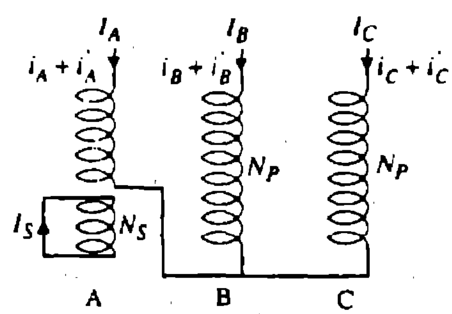


Figure 4.6 Three-phase, star-connected transformer with a short circuit between turns in phase A.

It is supposed that the currents flowing are as in Figure 4.6. The i's and the i''s represent the magnetizing currents, and they are neglected for the moment. The m.m.f.'s acting downwards on

the limbs are;

Limb A: $I_A(N_P - N_S) + I_S N_S$
Limb B: $I_B N_P$
Limb C: $I_C N_P$

Applying assumptions 2, 5 and 6 (m.m.f. balance between load currents) in section 4.2 it is found that;

$$I_A(N_P - N_S) + I_S N_S = \frac{1}{2}(I_B N_P + I_C N_P) \tag{4.32}$$

$$I_B N_P = \frac{1}{2}(I_C N_P + I_A(N_P - N_S) + I_S N_S) \tag{4.33}$$

$$I_C N_P = \frac{1}{2}(I_B N_P + I_A(N_P - N_S) + I_S N_S) \tag{4.34}$$

It is also clear that

$$I_A + I_B + I_C = 0 \tag{4.35}$$

If equation (4.34) is subtracted from (4.33) it is found that

$$I_B = I_C \tag{4.36}$$

If equation (4.35) and (4.36) are combined it is found that

$$I_B = I_C = -\frac{1}{2}I_A \tag{4.37}$$

When equation (4.32) and (4.37) are combined it is found that

$$\boxed{I_S = \left(-\frac{3N_P - 2N_S}{2N_S}\right)I_A} \tag{4.38}$$

From equation (4.37) and (4.38) it can be seen that apart from the sign the currents are single-phase. Let the phase of I_A be called phase α, where in the following argument a current 180° out of phase with I_A is for convenience said to be in phase with I_A, the difference being denoted by a minus sign.

All currents in phase with I_A, all fluxes induced by such currents, and all e.m.f.'s induced by such fluxes are said to be "in phase α". All currents, fluxes and e.m.f.'s 90° out of phase with the phase α-system are said to be "in phase β".

The e.m.f.'s induced by leakage flux arising from currents I_A, I_B, I_C and I_S are in phase α, and given by equation (4.14) and (4.15) in coils 1 and 2 on limb A. In coils B and C the e.m.f.'s is given by

$$j\omega L_{PP} I_B = j\omega L_{PP} I_C = -\frac{1}{2}j\omega L_{PP} I_A.$$

Since there is no resultant e.m.f. in coil 2, the core flux Φ_A in limb A must be in phase α. But Φ_A does not necessarily originate in limb A, and then the assumption that the core flux induced in a limb by a winding on it returns equally between the remaining limbs is not right. To solve this problem it is necessary to analyze the magnetizing currents and fluxes.

Let i_A, i_B and i_C denote the components of the magnetizing currents which are in phase α. If assumption 3 in section 4.2 is applied, the resultant magnetizing core fluxes have following α-components;

$$\text{Limb A:}\quad \Phi_{\alpha A} = \mathcal{P}'_{core}\left(i_A(N_P - N_S) - \frac{1}{2}(i_B N_P + i_C N_P)\right) \tag{4.39}$$

$$\text{Limb B:}\quad \Phi_{\alpha B} = \mathcal{P}'_{core}\left(i_B N_P - \frac{1}{2}(i_C N_P + i_A(N_P - N_S))\right) \tag{4.40}$$

$$\text{Limb C:}\quad \Phi_{\alpha C} = \mathcal{P}'_{core}\left(i_C N_P - \frac{1}{2}(i_B N_P + i_A(N_P - N_S))\right) \tag{4.41}$$

Another essential condition is that

$$i_A + i_B + i_C = 0 \tag{4.42}$$

$\Phi_{\alpha B}$ and $\Phi_{\alpha C}$ induce e.m.f.'s v_B and v_C in coils B and C which are in phase α, and are in the same ratio as the fluxes inducing them, since both coils has N_P turns. Hence the total e.m.f.'s in phase α in B and C are

$$V_B = v_B - \frac{1}{2}j\omega L_{PP} I_A \tag{4.43}$$

$$V_C = v_C - \frac{1}{2}j\omega L_{PP} I_A \tag{4.44}$$

V_C is in phase α, since the core and leakage fluxes inducing them are in phase α. But the supply voltage is three-phase, and therefore phase β e.m.f.'s must appear across coils B and C. In order to introduce them a system of phase β magnetizing currents, i'_A, i'_B and i'_C must flow, and the equations are

$$\text{Limb A:}\quad \Phi_{\beta A} = \mathcal{P}''_{core}\left(i'_A(N_P - N_S) - \frac{1}{2}(i'_B N_P + i'_C N_P)\right) \tag{4.45}$$

$$\text{Limb B:}\quad \Phi_{\beta B} = \mathcal{P}''_{core}\left(i'_B N_P - \frac{1}{2}(i'_C N_P + i'_A(N_P - N_S))\right) \tag{4.46}$$

$$\text{Limb C:}\quad \Phi_{\beta C} = \mathcal{P}''_{core}\left(i'_C N_P - \frac{1}{2}(i'_B N_P + i'_A(N_P - N_S))\right) \tag{4.47}$$

$$i'_A + i'_B + i'_C = 0 \tag{4.48}$$

But $\Phi_{\beta A}$ is zero since V_A has no phase β component. Then it follows that $i'_A = 0$, $i'_B = -i'_C$ and

$\Phi_{\beta B} = -\Phi_{\beta C}$. This gives the phase β e.m.f.'s across the limbs as $V_A' = 0$ and $V_B' = -V_C'$.

Figure 4.7 shows the voltage vector diagram of the system referred to the N as origin. V_A, V_B' and

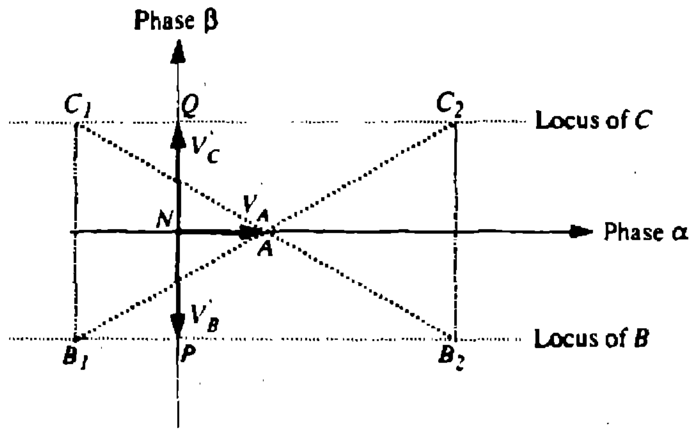


Figure 4.7 Construction of the voltage vector diagram of the system.

V_C' are represented by NA, NP and NQ respectively. Since the remaining components of B and C, namely V_B and V_C are in phase α, their locations must be on the lines shown. The applied e.m.f. is three-phase symmetrical, and the only solutions are AC_1B_1 or AB_2C_2 for its vector triangle. Whichever solutions is chosen $V_B=V_C$, and then it is found from equations (4.43) and (4.44) that $v_B=v_C$. It also follows that $\Phi_{\alpha B} = \Phi_{\alpha C}$. From equations (4.40), (4.41) and(4.42) it is found that this is true only if $i_B = i_C = -\frac{i_A}{2}$. Finally it is found that

$$\Phi_{\alpha B} = \Phi_{\alpha C} = -\frac{\Phi_{\alpha A}}{2} \tag{4.49}$$

The e.m.f. induced in coil 2 by leakage coupling is called E_2'. The total e.m.f. induced in coil 2 must be zero because it is short-circuited. This is equivalent to saying that sufficient magnetizing core flux, $\Phi_{\alpha A}$, must exist to induce an e.m.f. on $-E_2'$ in N_S turns of coil 2 and therefore $\frac{-E_2'(N_P-N_S)}{N_S}$ in coil 1. (The expression for E_2' is given in equation (4.15) on page 43). Total e.m.f. induced by $\Phi_{\alpha A}$ in phase A is $-E_2' - \frac{E_2'(N_P-N_S)}{N_S} = -\frac{E_2'N_P}{N_S}$. Since

$\Phi_{\alpha B} = \Phi_{\alpha C} = -\frac{\Phi_{\alpha A}}{2}$ it is found that

$$v_B = v_C = \frac{E_2' N_P}{2N_S} \tag{4.50}$$

From equation (4.17) on page 43 it is found that

$$\frac{1}{j\omega} V_A = L_{11} I_A + L_{12} I_S - \frac{N_P - N_S}{N_S} (L_{12} I_A + L_{22} I_S) \tag{4.51}$$

By combination of equation (4.43) and (4.50) it is found that

$$\frac{1}{j\omega} V_B = \frac{1}{j\omega} V_C = -\frac{1}{2} L_{PP} I_A + \frac{E_2' N_P}{2jN_S} = -\frac{1}{2} L_{PP} I_A + \frac{N_P}{2N_S} (L_{12} I_A + L_{22} I_S) \tag{4.52}$$

By combination of equation (4.16), (4.18), (4.51) and (4.52) it can be found (after some hard manipulation)

$$\frac{1}{j\omega} (V_A - V_B) = \frac{3}{2} I_A \left(\frac{3}{2} L_l - \frac{1}{2} L_{PP} + \frac{N_P}{N_S} (L_{12} + L_{22}) \right) \tag{4.53}$$

Figure 4.8 represents the complete voltage and current vector diagrams.

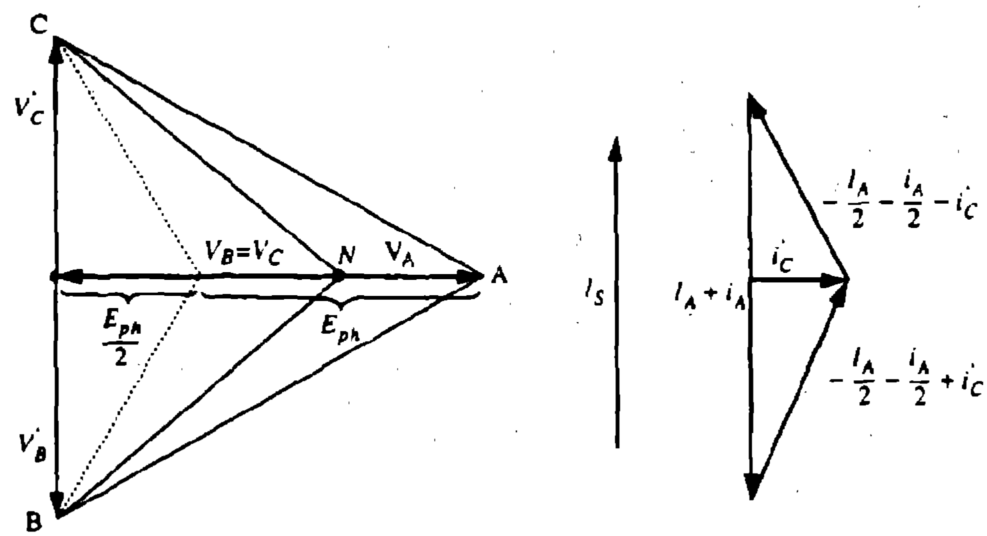


Figure 4.8 Voltage and current vector diagrams for the system.

From Figure 4.8 it is seen that if E_{ph} is the applied phase voltage

$$E_{ph} = \frac{2}{3}(V_A - V_B) \tag{4.54}$$

Referring to Figure 4.9, the accurate formula for I is given by

$$I = \frac{E_{ph}}{j\left(\frac{3}{2}X_l - \frac{1}{2}X_{0P} + \frac{N_P}{N_S}(X_{12} + X_{22})\right)} \tag{4.55}$$

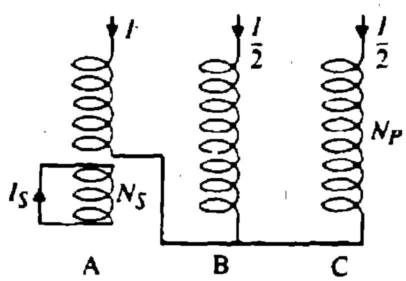


Figure 4.9 Three-phase, star-star connected transformer with a short-circuit between turns in phase A.

If it is written that $X_{0S} = \omega L_{22}$ the accurate formula for I is reduced to

$$\boxed{I = \frac{E_{ph}}{j\left(X_l + \frac{1}{2}\left(\frac{N_P}{N_S}\right)^2 X_{0S}\right)}} \tag{4.56}$$

4.4.2 Approximation

If it is assumed that the volts per turn induced by leakage flux in Figure 4.3(a) are the same for all the turns of the winding, then

$$\frac{j\omega(L_{12} + L_{22})I_P}{N_S} = \frac{j\omega(\overbrace{L_{11} + L_{22} + 2L_{12}}^{L_{PP}})I_P}{N_P}$$

$$\frac{N_P}{N_S} = \frac{L_{PP}}{L_{12} + L_{22}} \tag{4.57}$$

If approximation (4.57) is used in (4.55) the current is approximately given by

$$\boxed{I = \frac{E_{ph}}{j(\frac{3}{2}X_l + \frac{1}{2}X_{0P})}} \tag{4.58}$$

4.4.3 Correction for the winding resistance

In effect equation (4.58) reduces the analysis to that of an equivalent single-phase transformer in which an e.m.f. on $\frac{3}{2}E_{ph}$, (see Figure 4.8 on page 50), is applied to an inductive reactance $\frac{3}{2}(\frac{3}{2}X_l + \frac{1}{2}X_{0P})$ with an current I flowing. Then it is desirable to find the equivalent resistance. This will be done by calculating the total copper losses in the coils.

The total winding resistance of a coil with N_P turns is called R_{NP}. The copper losses of each of the coils in Figure 4.9 are as follows:

Coil 1: $\left(\frac{N_P - N_S}{N_P}\right)R_{NP}I^2$

Coil 2: $\left(\frac{N_S}{N_P}\right)R_{NP}I_S^2 = \left(\frac{3N_P - 2N_S}{2N_S}\right)^2\frac{N_S}{N_P}R_{NP}I^2$

Coil B: $R_{NP}(\frac{1}{2}I)^2$

Coil C: $R_{NP}(\frac{1}{2}I)^2$

The total copper losses in the coils are by addition found to be

$$P_{loss} = \left(\frac{3}{2}\left(\frac{3N_P}{2N_S} - 1\right)R_{NP}\right)I^2 \tag{4.59}$$

If equation (4.58) is to be amended the equivalent series resistance for E_{ph} applied is

$$R_{eq} = \left(\frac{3N_P}{2N_S} - 1\right)R_{NP} \tag{4.60}$$

Then the total expression for the current is approximately given by

$$\boxed{I = \frac{E_{ph}}{\left(\frac{3N_P}{2N_S} - 1\right)R_{NP} + j(\frac{3}{2}X_l + \frac{1}{2}X_{0P})}} \tag{4.61}$$

4.5 DELTA/STAR-CONNECTED THREE-PHASE TRANSFORMERS

4.5.1 Development of the equations

The arrangement is shown without magnetizing currents in Figure 4.10.

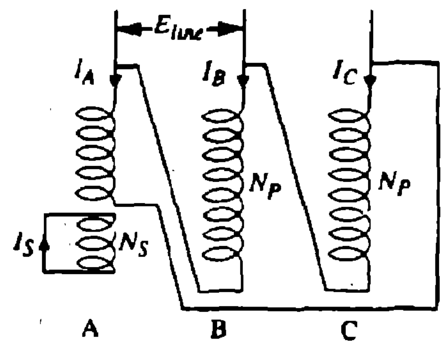


Figure 4.10 Three phase, delta/star-connected three-phase transformer with a short circuit between turns in phase A.

The ampere turns acting downwards the limbs are

Limb A: $I_A(N_P - N_S) + I_S N_S$
Limb B: $I_B N_P$
Limb C: $I_C N_P$

Applying assumptions 2, 5 and 6 in section 4.2 it is found that

$$I_A(N_P - N_S) + I_S N_S = \frac{1}{2}(I_B N_P + I_C N_P) \tag{4.62}$$

$$I_B N_P = \frac{1}{2}(I_A(N_P - N_S) + I_S N_S + I_C N_P) \tag{4.63}$$

$$I_C N_P = \frac{1}{2}(I_A(N_P - N_S) + I_S N_S + I_B N_P) \tag{4.64}$$

If equation (4.64) is subtracted from (4.63) it is found that

$$I_B = I_C = I \tag{4.65}$$

From equation (4.62) and (4.65) it is found that

$$I_A(N_P - N_S) + I_S N_S = I N_P \tag{4.66}$$

If the core flux is analyzed into circulating fluxes, Φ_{AB}, Φ_{BC} and Φ_{CA}, the e.m.f.'s induced by these fluxes are

Coil 1: $k(N_P - N_S)(\Phi_{CA} + \Phi_{AB})$ (4.67)

Coil 2: $kN_S(\Phi_{CA}+\Phi_{AB})$ (4.68)

Coil B: $kN_P(-\Phi_{AB}+\Phi_{BC})$ (4.69)

Coil C: $kN_P(-\Phi_{CA}-\Phi_{BC})$ (4.70)

The e.m.f.'s induced by leakage flux are given by equations (4.14) and (4.15) on page 43 for coil no. 1 and 2, and in coil B and C by

$$\dot{E_B} = \dot{E_C} = j\omega L_{PP}I \tag{4.71}$$

From Figure 4.10 it can be seen that coils 1, B and C in series form a closed circuit. Then it follows by addition that

$$\begin{aligned} 0 &= (k(N_P-N_S)(\Phi_{CA}+\Phi_{AB})+j\omega L_{11}I_A+j\omega L_{12}I_S)+(kN_P(-\Phi_{AB}+\Phi_{BC})+j\omega L_{PP}I) \\ &\quad +(kN_P(-\Phi_{CA}-\Phi_{BC})+j\omega L_{PP}I) \\ &= 2j\omega L_{PP}I-kN_S(\Phi_{CA}+\Phi_{AB})+j\omega L_{11}I_A+j\omega L_{12}I_S \end{aligned} \tag{4.72}$$

One other condition is that coil 2 is short-circuited.

$$0 = kN_S(\Phi_{CA}+\Phi_{AB})+j\omega L_{12}I_A+j\omega L_{22}I_S \tag{4.73}$$

If equation (4.72) and (4.73) are added and combined with equation (4.7) on page 41 it is found that

$$0 = (2I+I_A)L_{PP}+(I_S-I_A)(L_{12}+L_{22}) \tag{4.74}$$

Equation (4.74) and (4.66) leads to

$$0 = I\left(2L_{PP}+\frac{N_P}{N_S}(L_{12}+L_{22})\right)+I_A\left(L_{PP}-\frac{N_P}{N_S}(L_{12}+L_{22})\right) \tag{4.75}$$

4.5.2 Approximation

If it is assumed that the volts per turn induced by leakage flux in Figure 4.3(a) are the same for all the turns of the winding, then

$$\frac{N_P}{N_S} = \frac{L_{PP}}{L_{12}+L_{22}} \tag{4.76}$$

If approximation (4.76) is used in equation (4.75) it is found that

$$0 = I\left(2L_{PP}+\frac{N_P}{N_S}(L_{12}+L_{22})\right) \tag{4.77}$$

From this it follows that

$$I = I_B = I_C = 0 \tag{4.78}$$

This together with equation (4.66) gives that

$$\boxed{I_S = \frac{-I_A\,(N_P - N_S)}{N_S}} \tag{4.79}$$

From Figure 4.10 it is also seen that

$$\boxed{I_A = \frac{E_{line}}{jX_l}} \tag{4.80}$$

X_l is given by equation (4.18). Since $I = I_B = I_C = 0$, it is seen from Figure 4.10 that the line current in phase B is zero and the line current in phase A and B is the same as the current I_A.

From this it is seen that the damaged limb behaves as a single-phase transformer with the line voltage across its terminals, and the other limbs are unaffected.

4.5.3 Correction for the winding resistance

The analysis is also reduced to an equivalent single-phase transformer in which an e.m.f. on E_{line} is applied to an inductive reactance X_l with a current I_A flowing. Then it is desirable to find the equivalent resistance of this inductance. This will be done by calculating the total copper losses in the coils.

Since $I_B = I_C = 0$, the copper loss in these phases is zero. In the other coils the copper losses are as follows:

Coil 1: $\left(\frac{N_P - N_S}{N_P}\right) R_{NP} I_A^2$

Coil 2: $\left(\frac{N_S}{N_P}\right) R_{NP} I_S^2 = \left(\frac{N_P - N_S}{N_S}\right)^2 \frac{N_S}{N_P} R_{NP} I_A^2$

The total copper losses in the coils are by addition found to be

$$P_{loss} = \left(\left(\frac{N_P}{N_S} - 1\right) R_{NP}\right) I_A^2 \tag{4.81}$$

Then the equivalent series resistance for E_{line} applied is

$$R_{eq} = \left(\frac{N_P}{N_S} - 1\right) R_{NP} \tag{4.82}$$

Then the total expression for the current is approximately given by

$$\boxed{I_A = \frac{E_{line}}{\left(\frac{N_P}{N_S} - 1\right) R_{NP} + jX_l}} \tag{4.83}$$

This is the same expression as described with the equivalent circuit shown in Figure 5.13 on page 84 in section 5.7.2.

4.6 STAR/DELTA-CONNECTED THREE-PHASE TRANSFORMERS

4.6.1 Development of the equations

The arrangement is shown without magnetizing currents in Figure 4.11.

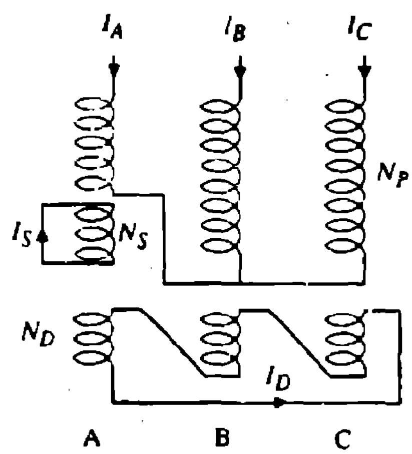


Figure 4.11 Three-phase, star/delta-connected transformer with a short circuit between turns in phase A.

The ampere turns acting downwards the limbs are

Limb A: $I_A (N_P - N_S) + I_S N_S + I_D N_D$
Limb B: $I_B N_P + I_D N_D$
Limb C: $I_C N_P + I_D N_D$

Another essential condition is that

$$I_A + I_B + I_C = 0 \tag{4.84}$$

Applying assumptions 2, 5 and 6 in section 4.2 it is found that

$$I_A (N_P - N_S) + I_S N_S + I_D N_D = \frac{1}{2} (I_B N_P + I_C N_P + 2 I_D N_D) \tag{4.85}$$

$$I_B N_P + I_D N_D = \frac{1}{2} (I_C N_P + 2 I_D N_D + I_A (N_P - N_S) + I_S N_S) \tag{4.86}$$

$$I_C N_P + I_D N_D = \frac{1}{2} (I_B N_P + 2 I_D N_D + I_A (N_P - N_S) + I_S N_S) \tag{4.87}$$

If equation (4.87) is subtracted from (4.86) it is found that

$$I_B = I_C \tag{4.88}$$

By combination of equation (4.84) and (4.88) it is found that

$$I_B = I_C = -\frac{1}{2} I_A \tag{4.89}$$

By combination of equation (4.85) and (4.89) it is found that

$$\boxed{I_S = \left(-\frac{3N_P - 2N_S}{2N_S}\right) I_A} \tag{4.90}$$

From this it is seen once again that the currents are single-phase.

The total e.m.f. around the delta winding is

$$j\omega (I_A L_{1D} + I_S L_{2D} + I_B L_{PD} + I_C L_{PD} + 3 I_D L_{DD}) = 0 \tag{4.91}$$

$$3 I_D L_{DD} = -I_A \left(L_{1D} - L_{PD} - \frac{3N_P - 2N_S}{2N_S} L_{2D}\right)$$

$$I_D = I_A \frac{\frac{N_P}{2N_S} L_{2D}}{L_{DD}} \tag{4.92}$$

In the terminology used above, I_D is in phase α. As before the phase β magnetizing currents are introduced to match the supply voltage. Further discussion is restricted to e.m.f.'s in phase α. The e.m.f. induced by leakage flux in coil 2 is given by

$$\frac{1}{j\omega} E_2' = I_A L_{12} + I_S L_{22} + I_D L_{D2} \tag{4.93}$$

Since coil 2 is short-circuited, it will as before be introduced sufficient core flux to balance the e.m.f. introduced by the leakage flux in coil 2. $\Phi_{\alpha A}$ induces an e.m.f. on $-E_2'$ in coil 2 and therefore $\frac{-E_2' (N_P - N_S)}{N_S}$ in coil 1. The total e.m.f. induced by $\Phi_{\alpha A}$ in phase A is

$$-E_2' - \frac{E_2'(N_P - N_S)}{N_S} = -\frac{E_2'N_P}{N_S} \tag{4.94}$$

Equation (4.49) on page 49 says that $\Phi_{\alpha B} = \Phi_{\alpha C} = -\frac{\Phi_{\alpha A}}{2}$, and then it is found that

$$v_B = v_C = \frac{E_2 N_P}{2N_S} \tag{4.95}$$

Introducing sufficient core flux to balance the leakage flux in coil 2 gives

$$\frac{1}{j\omega}V_A = L_{11}I_A + L_{12}I_S + L_{1D}I_D - \frac{N_P - N_S}{N_S}(L_{12}I_A + L_{22}I_S + L_{D2}I_D) \tag{4.96}$$

$$\frac{1}{\omega}V_B = \frac{1}{\omega}V_C = -\frac{1}{2}L_{PP}I_A + L_{PD}I_D + \frac{N_P}{2N_S}(L_{12}I_A + L_{22}I_S + L_{D2}I_D) \tag{4.97}$$

$$\boxed{\frac{1}{j\omega}(V_A - V_B) = \frac{3}{2}I_A\left(\frac{3}{2}L_l - \frac{1}{2}L_{PP} + \frac{N_P}{N_S}(L_{12} + L_{22})\right) - I_D\left(\frac{3N_P}{2N_S}L_{2D}\right)} \tag{4.98}$$

4.6.2 Approximation

The approximation to be made is to assume that the volts per turn induced by leakage flux are the same for all turns of the winding.

$$\frac{j\omega I_D L_{D2}}{N_S} = \frac{j\omega I_D L_{PD}}{N_P}$$

$$\frac{N_P}{N_S}L_{D2} = L_{PD} \tag{4.99}$$

Another approximation to be made is to suppose that the volts per turn induced by leakage flux in Figure 4.3(a) are the same for all turns of the winding

$$\frac{N_P}{N_S} = \frac{L_{PP}}{L_{12} + L_{22}} \tag{4.100}$$

In section 4.4 it was found that

$$E_{ph} = \frac{2}{3}(V_A - V_B) \tag{4.101}$$

If equation (4.98) is set into (4.101) it is found that

$$E_{ph} = j\omega I_A\left(\frac{3}{2}L_l - \frac{1}{2}L_{PP} + \underbrace{\frac{N_P}{N_S}(L_{12}+L_{22})}_{L_{PP}\text{ from (4.100)}}\right) - j\omega I_D\frac{N_P}{N_S}L_{2D} \tag{4.102}$$

By using equations (4.92) and (4.99) in (4.102) it is found that

$$\boxed{I_A = \frac{E_{ph}}{j(\frac{3}{2}X_l + \frac{1}{2}X_{0D})}} \tag{4.103}$$

X_{0D} is given by equation (4.31) on page 46.

4.6.3 Correction for the winding resistance

In effect equation (4.103) reduces the analysis to that of an equivalent single-phase transformer in which an e.m.f. on $\frac{3}{2}E_{ph}$ is applied to an inductive reactance $\frac{3}{2}(\frac{3}{2}X_l + \frac{1}{2}X_{0D})$ with a current I_A flowing. As in section 4.4 it is desirable to find the equivalent resistance. This will be done by calculating the total copper losses in the coils.

The copper losses of each of the coils in Figure 4.10 on page 53 are as follows:

Coil 1: $\left(\frac{N_P - N_S}{N_P}\right)R_{NP}I_A^2$

Coil 2: $\left(\frac{N_S}{N_P}\right)R_{NP}I_S^2 = \left(\frac{3N_P - 2N_S}{2N_S}\right)^2\frac{N_S}{N_P}R_{NP}I_A^2$

Delta coil: $3R_{ND}I_D^2 = 3R_{ND}\left(\frac{\frac{N_P}{2N_S}L_{2D}}{L_{DD}}I_A\right)^2 = \frac{3}{4}R_{ND}\left(\frac{L_{PD}}{L_{DD}}\right)^2 I_A^2$

Coil B: $R_{NP}(\frac{1}{2}I_A)^2$

Coil C: $R_{NP}(\frac{1}{2}I_A)^2$

The total copper loss in the coils are by addition found to be

$$P_{loss} = \frac{3}{2}\left(\left(\frac{3N_P}{2N_S} - 1\right)R_{NP} + \frac{1}{2}\left(\frac{L_{PD}}{L_{DD}}\right)^2 R_{ND}\right)I_A^2 \tag{4.104}$$

If equation (4.103) is to be amended the equivalent series resistance for E_{ph} applied is

$$R_{eq} = \left(\frac{3N_P}{2N_S} - 1\right)R_{NP} + \frac{1}{2}\left(\frac{L_{PD}}{L_{DD}}\right)^2 R_{ND} \tag{4.105}$$

Then the total expression for the current is approximately given by

$$\boxed{I_A = \frac{E_{ph}}{\left(\frac{3N_P}{2N_S} - 1\right)R_{NP} + \frac{1}{2}\left(\frac{L_{PD}}{L_{DD}}\right)^2 R_{ND} + j\left(\frac{3}{2}X_l + \frac{1}{2}X_{0D}\right)}} \tag{4.106}$$

4.7 TESTS IN THE LABORATORY

Some measurements performed in the laboratory with short circuits between turns on a three-phase transformer will in this section be used together with the equations evolved for the star/star and delta/star connected transformers. The motivation for the combination of the equations and results from the measurements is to try to find the order of magnitude of the parameters in the equations, and see if the results are in reasonable accordance with each other.

4.7.1 A brief description of the test arrangement

Before the full scale tests with short circuits between turns or layers in the high voltage coil were carried out at "Munkvoll", some tests were done in the laboratory with one of the transformers. It was a 300 kVA transformer designed for 11.43/0.235 kV, star/star connection, or 6.6/0.235 kV, delta/star connection. The rated primary current for this transformer was $I_N = 15.15\ A$, and the rated magnetizing current was $I_{m,N} = 0.19\ A$. The primary coils were of the layer type, and the total number of turns in each primary coil was $N_P = 1074$. The number of short-circuited turns (N_S) in phase A was 1, 3, 26, 52 or 78. In the tests with 1 or 3 turns short-circuited, a conductor was wrapped around coil A 1 or 3 times, respectively. In the cases with 26, 52 and 78 turns short-circuited, the short circuit was established at the tappings. The short circuit was established with the same type of short circuiter as shown in Figure 7.4 on page 113 in section 7.2.3.

To avoid the influence of the inrush currents, the short circuit was established approximately 30 seconds after the transformer was energized. Following parameters were measured:

- The line currents in each phase.
- The current in the short-circuited part of coil A.
- The voltages across each coil.

All the values that will be presented here are calculated true r.m.s. values. They are calculated over the first 13 electrical periods after the short circuit was established.

Tests with following conditions were done:

- $E_{line} = 6.6\ kV$, Delta/star connected.
- $E_{line} = 6.6\ kV$, Star/star connected.
- $E_{line} = 11.43\ kV$, Star/star connected.

In all the tests the low voltage side of the transformer was no-loaded.

4.7.2 Results from the measurements

Table 4.1 presents some of the results from the measurements.

N_S	Delta/star $E_{line} = 6.6\ kV$		Star/star $E_{line} = 6.6\ kV$		Star/star $E_{line} = 11.43\ kV$	
	$I_A\ [A]$	$I_S\ [A]$	$I_A\ [A]$	$I_S\ [A]$	$I_A\ [A]$	$I_S\ [A]$
1	1.52	1364	0.71	1070	1.09	1363
3	4.82	1602	2.12	1101	3.52	1655
26	36.8	1429	9.85	591	22.4	1188
52	68.6	1220	12.7	384	31.9	820
78	125	1324	15.8	316	42.5	707

Table 4.1 Line current (I_A) and current in the short-circuited part of the transformer (I_S) with different connection and supply voltage.

It is seen that the line current is increasing fast by increase of the number of short-circuited turns. But it is also seen that it is necessary to have a given number of short-circuited turns before the line current approaches the rated primary current of the transformer. When this transformer is delta/star connected it is expected from the measurements that the primary rated current will be reached if about 11 turns are short-circuited[1]. From the measurements it is also seen that it is necessary to have more turns short-circuited to reach the rated primary current when the transformer is star/star connected.

In the tests with only 1 or 3 turns short-circuited, the value of the ohmic resistance in the short-circuited part of the coil is very difficult to calculate, because the contact resistance can be in the same order as the resistance of one turn.

For later use in equations (4.61) on page 52 and (4.83) on page 56, $R_{NP} = 2.49\ \Omega$ for the coils in this transformer.

1. This is about 1% of the turns on one limb.

4.7.3 The validity of the assumption of m.m.f. balance

The difference between the measured values for I_A and the values calculated with the assumption of m.m.f. balance between the currents (equation (4.38) on page 47 and (4.79) on page 55) has been calculated. The results are shown in Table 4.2.

N_S	Delta/delta $E_{line} = 6.6\ kV$ $\left(\frac{I_{A,meas}}{I_{A,calc}} - 1\right)100$ [%]	Star/star $E_{line} = 6.6\ kV$ $\left(\frac{I_{A,meas}}{I_{A,calc}} - 1\right)100$ [%]	Star/star $E_{line} = 11.43\ kV$ $\left(\frac{I_{A,meas}}{I_{A,calc}} - 1\right)100$ [%]
1	19.6	7.0	29.3
3	7.4	3.1	14.1
26	3.6	1.6	14.9
52	10.5	-0.6	16.4
78	20.5	-1.7	18.2

Table 4.2 Percentage divergence from m.m.f. balance in the currents.

4.7.4 Consideration of X_l and X_{0P} by help of the measurements in the laboratory

It is desirable to determine X_l and X_{0P} used in equation (4.61) on page 52 and (4.83) on page 56 by help of the measurements described in section 4.7.2. X_l will be calculated by using equation (4.83) together with the measurements on the delta/star connected transformer. Due to the uncertainty in the ohmic resistance with 1 or 3 turns short-circuited, X_l will only be calculated for the cases with 26, 52 and 78 turns short-circuited. The results are shown in Table 4.3.

N_S	$\left(\frac{N_P}{N_S} - 1\right)R_{NP}$ [Ω]	X_l [Ω]
26	100	149
52	48.9	82.8
78	31.8	42.1

Table 4.3 Values for X_l found by help of measurements on the delta/star connected transformer and equation (4.83) on page 56.

As it was the same transformer that was used for the delta/star and the star/star measurements, X_l found in Table 4.3 can be used together with the measurements on the transformer when it was star/star connected to calculate X_{0P}. The results are presented in Table 4.4. In these calculations it is assumed that the right values of X_l are the values calculated for the delta/star connected transformer.

N_S	$\left(\frac{3N_P}{2N_S}-1\right)R_{NP}$	Star/star $E_{line} = 6.6\ kV$		Star/star $E_{line} = 11.43\ kV$	
		$\frac{3}{2}X_l+\frac{1}{2}X_{0P}$	X_{0P}	$\frac{3}{2}X_l+\frac{1}{2}X_{0P}$	X_{0P}
	$[\Omega]$	$[\Omega]$	$[\Omega]$	$[\Omega]$	$[\Omega]$
26	151.8	356	265	253	58
52	74.6	290	332	193	138
78	48.9	237	348	147	168

Table 4.4 Calculated values of the parameters in the equations by help of measurements.

If the conditions had been as in the assumptions described in section 4.2, $\frac{3}{2}X_l+\frac{1}{2}X_{0P}$ should have been the same for the star/star connected transformer for $E_{line} = 6.6\ kV$ and $E_{line} = 11.43\ kV$. But it is seen that the lowest values of $\frac{3}{2}X_l+\frac{1}{2}X_{0P}$ is for $E_{line} = 11.43\ kV$. The main reason for this must be the non-linearity in the transformer core. Then the currents are no longer increasing linearly with the applied voltage. One of the assumptions in the calculation model was to neglect the non-linearity in the transformer core. From the measurements it is also seen that the divergence caused by the non-linearity is increasing when the number of short-circuited turns is increasing. Due to the saturation in the core, the magnetizing currents are heavily increased, and this results in increased line currents.

Then it seems to be clear that the core saturation can not be neglected when larger parts of a coil are short-circuited. Under normal working conditions for distribution transformers, the magnetizing currents are heavily increased with a small increase in the supply voltage.

4.7.5 Comparison of the results for star/star and delta/star connected transformers

If equation (4.61) on page 52 is compared to equation (4.83) on page 56 it is found that

$$\frac{I_\Delta}{I_Y} = \frac{E_{line,\Delta}\left(\left(\frac{3N_P}{2N_S} - 1\right)R_{NP} + j\left(\frac{3}{2}X_l + \frac{1}{2}X_{0P}\right)\right)}{E_{ph,Y}\left(\left(\frac{N_P}{N_S} - 1\right)R_{NP} + jX_l\right)} \tag{4.107}$$

If it is supposed that $\frac{3N_P}{2N_S} - 1 = \frac{3N_P}{2N_S}$ it is found that

$$\frac{I_\Delta}{I_Y} \geq \frac{3}{2} \cdot \frac{E_{line,\Delta}}{E_{line,Y}} \tag{4.108}$$

The results are shown in Table 4.5.

N_S	1	3	26	52	78
$\frac{I_\Delta}{I_Y}$	1.39	1.37	1.64	2.15	2.94
$E_{line} = 6.6\ kV$ for I_Δ $E_{line} = 11.43\ kV$ for I_Y					

Table 4.5 The ratios of the measured currents for the delta/star and the star/star connected transformers.

Equation (4.108) shows that the ratios should have been more than 1.5. The star connected transformer with an unearthed neutral allows the neutral potential to float with respect to ear and this reduces the voltage at the short circuit when the number of short-circuited turns i increasing.

4.8 Conclusions

Some general conclusions from this chapter are:

- Equations describing the relations between currents and applied voltages for single- and three-phase transformers are developed, when given fractions of the primary winding are short-circuited.
- When the fault occurs on the primary winding the short-circuited turns act as an auto-transformer load on the winding.
- The position and number of the short-circuited turns affect the primary current drawn from the line.

- When relatively few turns are short-circuited, extremely large currents flow in the short-circuited turns, while relatively small currents are drawn from the primary lines. The high currents in the few short-circuited turns are due to the low impedance between those turns and the primary winding, while the smallness of the currents drawn from the primary lines is due to the high ratio of total primary turns to short-circuited turns.
- For a given number of turns short-circuited the impedance is a minimum when the axial centre of the turns coincides with the centre of the winding, and the line current is then a maximum for that number of turns.
- The inductances used in the equations can not be calculated analytically.
- The equations evolved are presumably of little practical use.
- The assumption to neglect the non-linearity of the transformer core entails big errors when larger parts of a coil are short-circuited. Because of the saturation in the core, the magnetizing currents are heavily increased, and this results in increased line currents.
- The development of the equations helps to increase the knowledge and understanding of what is happening electrically when there is a short circuit between turns in a transformer.

Star/star-connected transformers:

The relation between the line current (I_A) in the faulty phase and the current in the short-circuited turns (I_S) is given as

$$I_S = \left(-\frac{3N_P - 2N_S}{2N_S}\right)I_A \tag{4.109}$$

Measurements have shown that equation (4.109) is almost right when the induction in the transformer is low, but the deviation increases with increasing induction.

The fault current in the two other phases is given as $I_B = I_C = -\frac{1}{2}I_A$. The expression for the line current in the faulted phase is given in equation (4.61) on page 52.

Delta/star connected transformers:

The relation between the current in the faulty phase (I_A) and the current in the short-circuited turns is given as

$$I_S = \left(-\frac{N_P - N_S}{N_S}\right)I_A \tag{4.110}$$

Measurements have shown that the equation is almost right. The current in the two other phases, (I_B) and (I_C), is zero. The expression for the current in the faulty phase is given in equation (4.83) on page 56.

It is found that the damaged limb behaves as a single-phase transformer with the line voltage

across its terminals, and the other limbs are unaffected.

Star/delta connected transformers:

The relation between the current in the faulted phase and the current in the short-circuited turns is the same as shown in equation (4.109). Also with this connection the line currents in the two other phases are found to be $I_B = I_C = -\frac{1}{2}I_A$. The expression for the current in the faulty phase is given in equation (4.106) on page 60. No measurements on a transformer with this connection have been carried out in this work.

5 EXPERIMENTS WITH SHORT CIRCUITS BETWEEN TURNS ON A SINGLE-PHASE MODEL TRANSFORMER

5.1 SUMMARY

To carry out preliminary studies of what is happening when an internal short circuit is established between turns in transformer windings, a single-phase, oil-filled transformer was built. The transformer tank was equipped with transparent polycarbonate windows, and video recordings were taken to study the course of events on the exterior of the coils during the tests. Conducted work was done by two diploma students [43].

Electrical equivalent circuits for the transformer with two kinds of faults are evolved. They will be used to calculate currents and temperatures in the short-circuited part of the winding.

Tests have been carried out with short circuits between turns in the medium voltage coil in this single phase model transformer. Gas bubbles were produced around the short-circuited turns during the tests. It was observed that the amount of gas increased with the power evolved in the short-circuited turns. Large parts of the coils were destroyed in the tests. Turns melted, and in many cases other turns were involved in the short circuit and destroyed. Typically, craters in the coils were created, and melted copper tended to flow outwards in the coils. Observations made it clear that large forces between the short-circuited and the healthy part of the coils had been present.

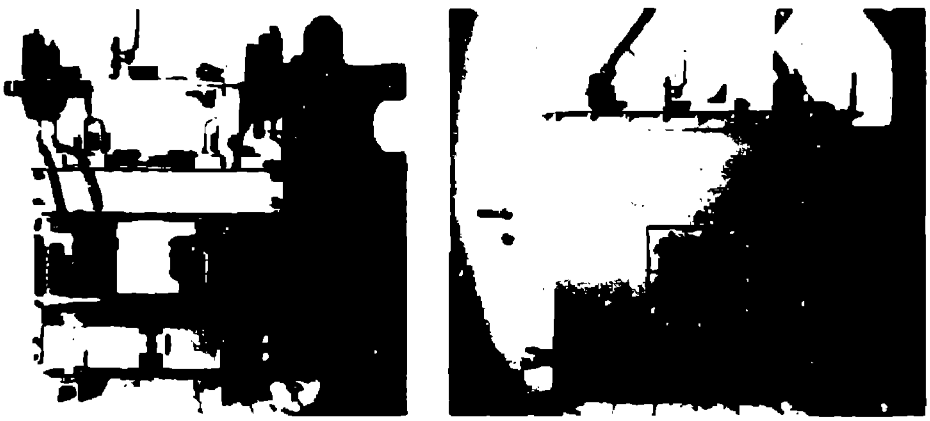
Electrical equivalent circuits for the transformer are developed with validity for the situation with a few or many turns short-circuited. From the measurements it is seen that the leakage reactance is decreasing very much when the number of short-circuited turns is increased. Since the resistance is also decreasing, this means that the line current is increasing very fast when the number of short-circuited turns is increased.

By a combination of the equivalent circuits and measurements on the model transformer, the average temperature in the short-circuited turns is calculated to be about 6-700 °C at the time when the faults developed further.

The results from the tests on the model transformer were relevant to, and valuable in the design of the full scale test setup described in chapter 7.

5.2 DESCRIPTION OF THE SINGLE-PHASE MODEL TRANSFORMER

The basis for the model was a three-phase, star/star connected, 315 kVA, 12/0.24 kV distribution transformer with four crossover coils in each medium voltage winding. In the model one or two of these crossover coils served as the medium voltage coil. The transformer core had two limbs, with the so called "split-core" design[1]. The transformer is shown in Figure 5.1



(a) (b)

Figure 5.1 Pictures of the single-phase transformer.
(a) shows the transformer core and the windings. The medium voltage coil is placed on the right limb, and the low voltage coil on the left limb.
(b) shows the transformer when it is placed inside the "transformer tank".

The dimensions of the "transformer tank" were:
$(length \times width \times height) = (0.7 \times 0.43 \times 0.7)\ m^3 = 0.21\ m^3$. Pressure relief devices with settings on 0.4 bar overpressure were installed. Before each test the tank was completely filled with mineral transformer oil.

5.2.1 The cross section of the core

With $N = 230$ turns, an applied voltage $E = 1840\ V$ and a magnetic flux density $B_f = 1.7\ T$, the cross section of the core was calculated to be

$$A_{core} = \frac{\sqrt{2}E}{N\omega B_f} = 0.0212\ m^2 \tag{5.1}$$

The cross section of the core was quadratic, and the width of the metal sheets was 14.5 cm. The core was made of standard oriented steel.

5.2.2 The construction of the medium voltage coils

In the model tests 3 different medium voltage coils were used.

1. It was constructed in this way because it had to be easy to replacing the medium voltage coil

Common key data for the 3 medium voltage coils:

Conductor	: $\varnothing = 3$ mm copper
Conductor insulation	: Polyesterimid varnish, thickness 0.07 mm
Layer insulation	: 2 layers with 0.05 mm paper with density 43 $\frac{g}{m^2}$
Inner diameter of the coil	: ~226 mm
Voltage per turn	: ~8 V

Additional data for coil 1:

Total number of turns	: 230
Number of turns per layer	: ~23
Number of layers	: 10

Additional data for coil 2:

Total number of turns	: 370
Number of turns per layer	: ~30
Number of layers	: ~12

Additional data for coil 3:

Total number of turns	: 95
Number of turns per layer	: ~16
Number of layers	: 6

Coil 1 is shown in Figure 5.2. Coil 2 and 3 are constructed in the same way, the only difference is the number of turns.

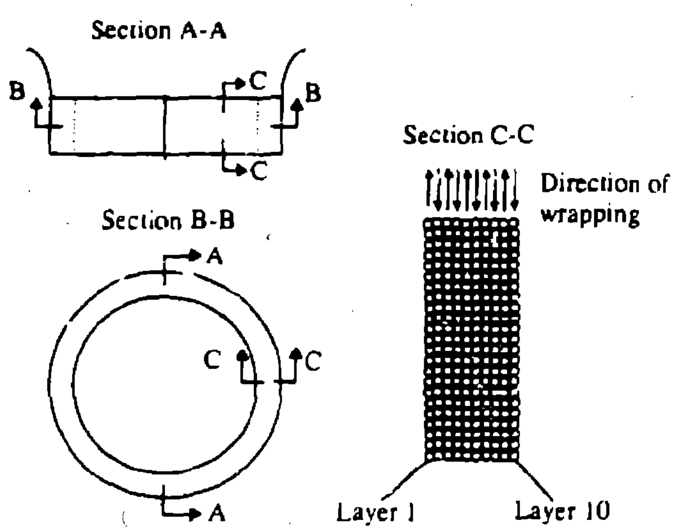


Figure 5.2 Three sections of the medium voltage coil (coil 1).

5.2.3 Establishment of the short circuit

The short circuit was established in two different ways:

Short circuit established by a clamp:

This method is shown in Figure 5.3.

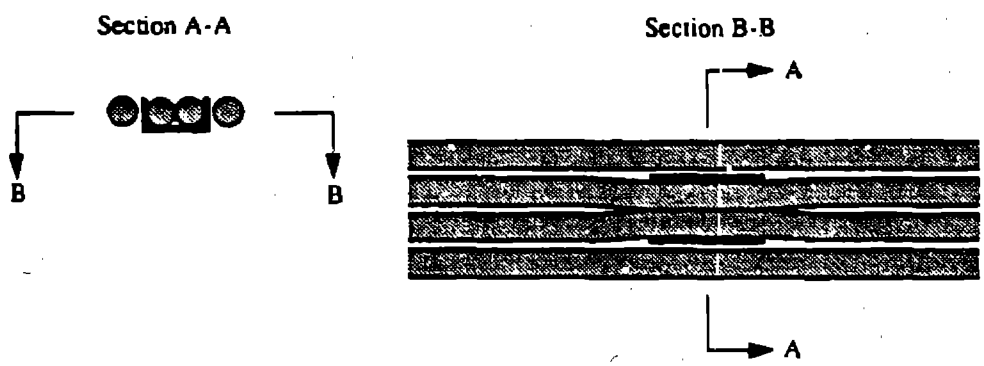


Figure 5.3 Short circuit established by a copper clamp.

The insulation varnish was removed from the conductors at the place where the clamp was placed. The clamp was equipped with spikes, and the metallic contact between the short-circuited turns was good.

Short circuit established without a clamp

This method is shown in Figure 5.4.

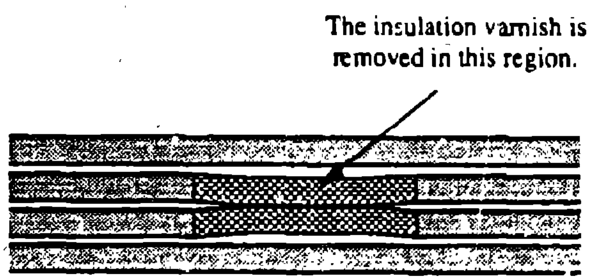


Figure 5.4 Short circuit established by contact between the conductors.

The insulation varnish was removed from the conductors at the place where the short circuit was established (about 2 centimeters). Contact between the two turns was established when the

conductors were bent towards each other in the area with removed varnish.

5.2.4 Rated data for the transformer

In the tests the coils were placed on the limb in 3 ways. In this section the arrangements will be called test arrangement 1, 2 and 3 respectively. See Figure 5.5.

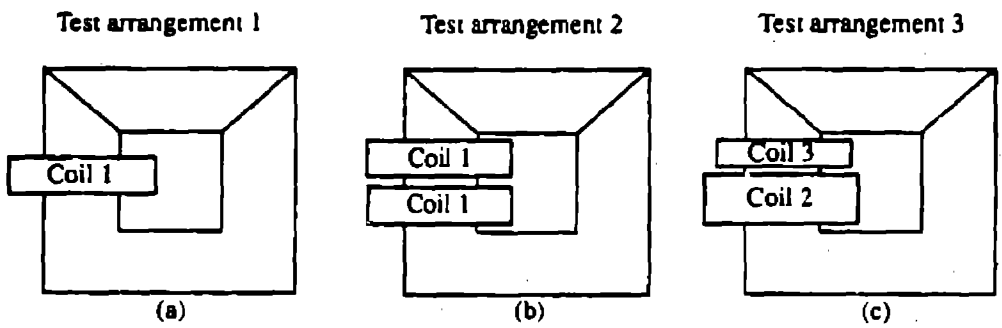


Figure 5.5 The three different test arrangements used in the model tests. (The LV coil was placed on the right limb, but it is not shown on the sketches.

With one medium voltage coil (test arrangement 1) the transformer had following rated data:

- $S_N = 27.6 kVA$
- $U_{N,P} = 1840\ V$
- $I_{N,P} = 15.2\ A$
- Voltage ratio: $1840/230 = 8$

With two medium voltage coils in series (test arrangement 2 and 3), the transformer had following rated data:

- $S_N = 55.2\ kVA$
- $U_{N,P} = 3680\ V$
- $I_{N,P} = 15.2\ A$
- Voltage ratio: $3680/230 = 16$

5.3 EXPERIMENTAL ARRANGEMENT FOR THE MEASUREMENTS

The tests were carried out in the "High Current Laboratory" at NTH/EFI. To obtain the wanted supply voltage for the single phase transformer, it was necessary to have two transformers in series in the supply circuit. Because of these transformers the short circuit reactance became comparatively large.

5.3.1 Schematic description of the test arrangement

The test arrangement is shown in Figure 5.6.

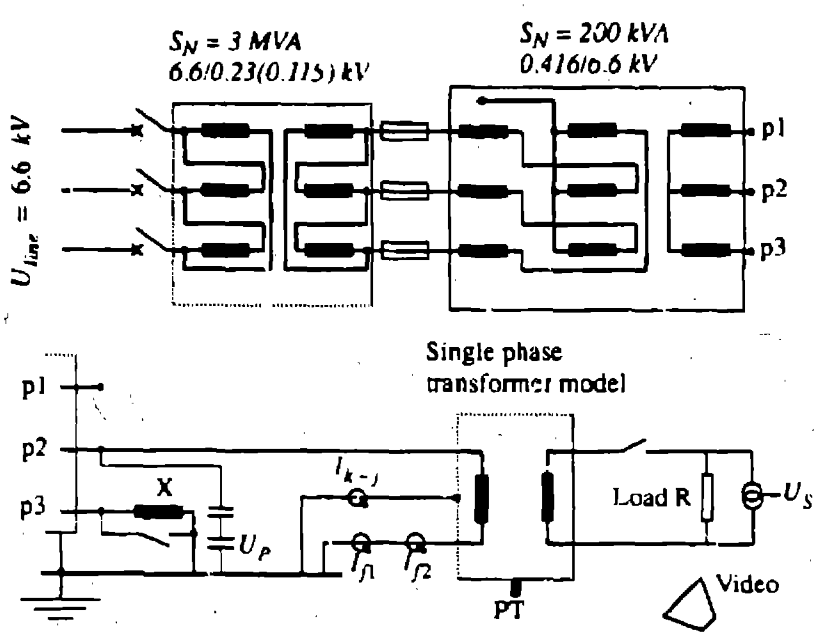


Figure 5.6 Schematic description of the test arrangement for the single-phase transformer model.

In Figure 5.6 the following abbreviations are used:

PT	: Pressure transmitter
X	: Reactor in series with the test object to limit the current
R	: Load resistance

Current measurements:

The currents were measured with current transformers (I_{k-j} and I_{f1}) and Rogowski-coil (I_{f2}).

Voltage measurements:

The voltage on the primary side of the transformer (U_P) was measured with a capacitive divider. The voltage on the secondary side was measured with a voltage transformer.

Pressure transmitter:

The pressure was measured with both piezoresistive transmitters and an oil column placed on the cover of the transformer.

5.3.2 Signal transmission, data sampling and data storage

Figure 5.7 gives a description of the signal transmission system. The measuring instruments (voltage divider, current transformer etc.) and the electrical to optical transmitters were placed in the laboratory. The optical to electrical receivers, the transient recorders and the PC were placed in the control room. All signals were transmitted to the control room by optical fibres.

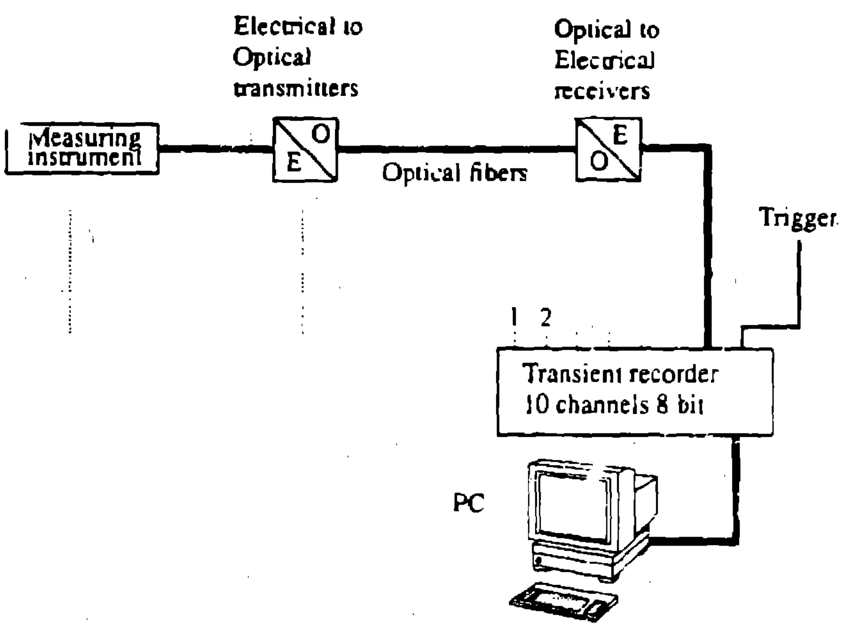


Figure 5.7 Schematic description of the signal transmission system used in the high current laboratory.

The maximum memory for each channel was 65 kb. Since the memory was limited, and a measuring time of about 30 seconds was wanted, the sampling frequency was as low as 2 kHz.

5.4 A SURVEY OF TYPE OF SHORT CIRCUITS TESTED

Table 5.1 on page 75 gives a survey of type of short circuits and arrangements in the tests. The three different test arrangements are shown in Figure 5.5 on page 71.

5.5 A SURVEY OF THE COURSE OF EVENTS IN THE TESTS

No detailed description of the course of events in each test will be presented. Only the distinctive features from the model tests are presented.

5.5.1 Tests with short circuits between neighbouring turns in the same layer

Table 5.2 gives a survey of some of the results from the test with short circuits between neighbouring turns in the same layer.

Test no.	t_1 [sec]	$W_{in} - W_{load}$ [kWs]	Max pressure [mbar]	Fault evolution	Type of destruction of the coils: Layers with melted or welded turns (layer no.)	Type of destruction of the coils: Layers with damaged insulation varnish (layer no.)
1	5.7	39.8	-	A	10	10
2	5.6	59	2	A	10	10
3	1.6	19	4	B	9	9, 10
4-6	1.5	-	7-29	B	3-7	3-7
7	1.4	17.9	8	B	5, 6	4-7
8	1.9	18.2	26	B	5, 8	4-8
9	1.6	19.4	66	B	5, 7	5-8
10	1.45	18.7	262	C	2, 6	2-6
11	1.36	16.6	95	B	2, 6	2-6

t_1: Time until other turns were involved in the short circuit, or until the turn melted off.
$W_{in} - W_{load}$: The energy evolved in the transformer until $t = t_1$.
Fault evolution A: The short-circuited turn melted off.
Fault evolution B: Other turns were involved in the short circuit.
Fault evolution C: Fluctuating fault with other turns involved in the short circuit.

Table 5.2 Results from the tests with short circuits between neighbouring turns in the same layer.

Test no.	Arr. no	Type of short circuit		Short circuit with clamp	Location of short circuit	Loaded trans-former	Comments
		Between turns	Between layers				
1	1	x		x	M 10		
2	1	x		x	M 10	x	
3	1	x		x	M 9		
4-6	1	x		x	M 5		3 tests with the same coil
7	1	x		x	M 5		
8	1	x			M 5	x	
9	1	x		x	L 5		
10	3	x		x	M 3		
11	3	x			M 3		
12	1		x (21)	x	L 9+10		
13	1		x (22)	x	L 5+6		No measurements
14	1		x (21)	x	L 5+6		
15	1		x (46)	x	4+5		
16	2		x (21)	x	U 5+6		
17	3		x (20)	x	L 3+4		
18	3		x (22)		L 3+4		
19	3		x (22)	x	L 3+4		Without layer insulation. No measurements
20	3		x (22)	x	L 3+4		Without layer insulation

M: middle part of the coil
L: lower part of the coil
U: upper part of the coil
Number of short-circuited turns in parenthesis.

Table 5.1 A survey of type of short-circuits and arrangements in the model tests.

Short circuit in the outermost layer:

In two tests (test 1 and 2) the short-circuited turn melted off, and the fault did not develop further. In both tests the short-circuited turn was situated in the outermost layer. The short-circuited turn melted off 5.5 and 5.6 seconds, respectively, after the voltage was turned on. In test 1 the current was flowing through the short circuit clamp after the short-circuited turn melted off, and the transformer worked as normal (with one turn less than normal). See Figure 5.8(a).

In test 2 the transformer worked normally after the short-circuited turn melted off. Contact was established between two neighbouring turns where the varnish was damaged by the high temperature in the short-circuited turn. As a result the current started to flow as shown in Figure 5.8(b).

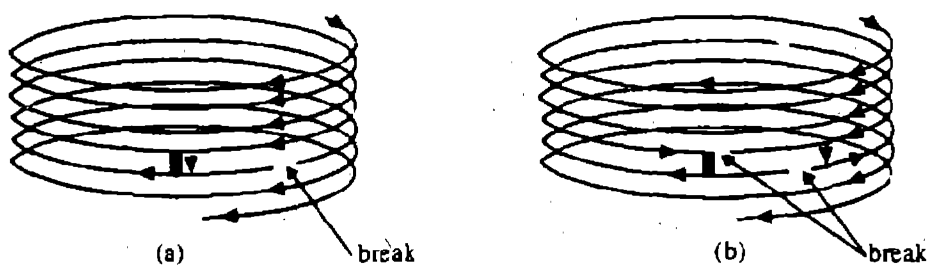


Figure 5.8 (a) The situation after the short-circuited conductor melted off.
(b) The situation after the short-circuited turn melted off, and contact was established between two neighbouring turns where the varnish was damaged.

At the break in the conductor, shown just by the clamp in Figure 5.8(b), one millimeter of the conductor was replaced with solder. This was done in an attempt to attain a series fault requiring a high coil voltage in order to continue. It was expected that the solder would melt and disappear from the gap between the conductors before the varnish on the copper conductor was damaged by the high temperature in the short-circuited turn. In the test the solder melted, but it did not disappear from the gap before the varnish was damaged. The short-circuited turn melted off on two places, but contact was established to the neighbouring turn as shown in Figure 5.8(b). The transformer then worked as normal again, with about one turn less than normal.

It seems as a short circuit between two neighbouring turns in the outermost layer does not necessarily develop further. When the short-circuited turn is melted off, there can be a break in the coil, or contact can be established through direct metallic contact between turns, or through carbon after the varnish (or other insulation materials) was burned. When the short-circuited turn is in the outermost layer, the contact area towards the other turns is less than in the case when the short-circuited turn is situated in layers inside the coil.

In the tests with the short-circuited turn in the outermost layer, gas-bubbles were produced just after the voltage was turned on (~0.5 sec.). The quantity and size of the gas bubbles increased with time until the short-circuited turn melted off.

Short circuit in layers inside the coil:

In tests no.3, 4, 7, 8, 9, 10 and 11 short circuit between neighbouring turns developed further. The time from the voltage was turned on until other turns were involved in the short circuit varied from 1.36 to 1.9 sec. In test no.8 (where the time was 1.9 sec.) the low voltage side of the transformer was loaded with a resistance $R = 1.4\ \Omega$. From the measurements it is seen that because of the voltage drop in the supply circuit, the applied voltage on the transformer in this test was lower than in the other tests (3, 4, 7 and 9). This is likely the reason why the time to the further developing of the fault was longer in test no.8 compared to the other tests.

In these tests gas bubbles started to flow from the coil about at the same time as the fault developed further in the coil (a little bit earlier).

5.5.2 Tests with short circuits between layers

Table 5.2 gives a survey of some of the results from the tests with short circuits between layers. In

Test no.	t_2 [sec]	$W_{in} - W_{load}$ [kWs]	Max pressure [mbar]	Fault evolution	Type of destruction in the coils: Layers with melted or welded turns (layer no.)	Layers with damaged insulation varnish (layer no.)
12	-	-	5	D	-	9, 10
13	No measurements		~60	?	-	5, 6
14	16.8	401	59	E	-	4-7
15	-	-	3	-	-	-
16	4.1		130	D,E	4-7	4-7
17	4.6	361	437	E	2-4	2-5
18	5.1	389	242	E	2-5	1-5
19	No measurements					
20	-	-	186	D	-	-

t_2: Time until other turns were involved in the short circuit, or until the turn melted off.
$W_{in} - W_{load}$: The energy evolved in the transformer until $t = t_2$.
Fault evolution D: Earth fault.
Fault evolution E: Other turns were involved in the short circuit.

Table 5.3 Results from the tests with short circuits between layers.

test no. 12 and 16 the coils moved during the tests, and short circuits to earth were established. It is seen that the fault developed further much faster with test arrangement 2 and 3 in Figure 5.5 on page 71 compared to test arrangement 1. With test arrangement 2 and 3 a larger part of the coil was involved in the short circuit 4.1 to 5.1 sec. after the voltage was turned on. With test arrangement 1 the time was 16.8 sec.

In test no.15 about 20% of the turns was short-circuited (test arrangement 1 in Figure 5.5 on page 71). The current was about the same as if the primary terminals of the transformer had been short-circuited, and the supply voltage was very low. The coil was not destroyed during the test.

When the short circuit was established between the outermost layers (test no. 12), small gas bubbles were observed about 1 sec. after the voltage was turned on. The quantity and size of the bubbles increased with time. At t=4.2 sec. the short-circuited turns and the healthy part of the coil separated, the healthy part moved upwards and the short-circuited part moved downwards. This happened very fast, and it clearly shows that the forces were large.

In test no 13 and 14 (test arrangement 1) bubbles were observed from 4 and 7 sec., respectively, after the voltage was turned on. The quantity and size of the bubbles increased with time. Most of the bubbles came from the upper and lower part of the coil. Big bubbles did also evolve from the coils for some time after the voltage was turned off.

In test no. 16 (test arrangement 2), 17 and 18 (test arrangement 3) big quantities of gas bubbles were observed 3.6-5 sec. after the voltage was turned on.

In test no. 19 and 20 there was no paper insulation between the layers. Bubbles started to flow from the coils about 4 seconds after the voltage was turned on.

5.5.3 Arcs during the tests

In 3 tests the coils moved during the tests because they were not sufficient mechanically secured. This resulted in earth faults or arcs between the coils and the transformer core.

In many of the tests light flashes from the coils were observed. Sometimes this was followed by black oil and large quantities of gases. These light flashes may have been caused by glowing, melted copper or from arcs in the coils.

Test no.3 gave an indication of the presence of arcs in the coil. See Figure 5.9. The figure shows the voltage and current during the test when the short circuit between layers had developed further involving other turns in the short circuit. The voltage at point 2 and 3 indicates that an arc tries to be extinguished. The peak in the voltage at point 2 is found to be at the zero passage of the current. At point 3 it is seen that the arc was near to be extinguished, in other words, the current was near to be zero for one half electrical period.

5.5.4 Audible noise from the transformers

Differences in the audible noise from the transformers were easy to observe, depending on the

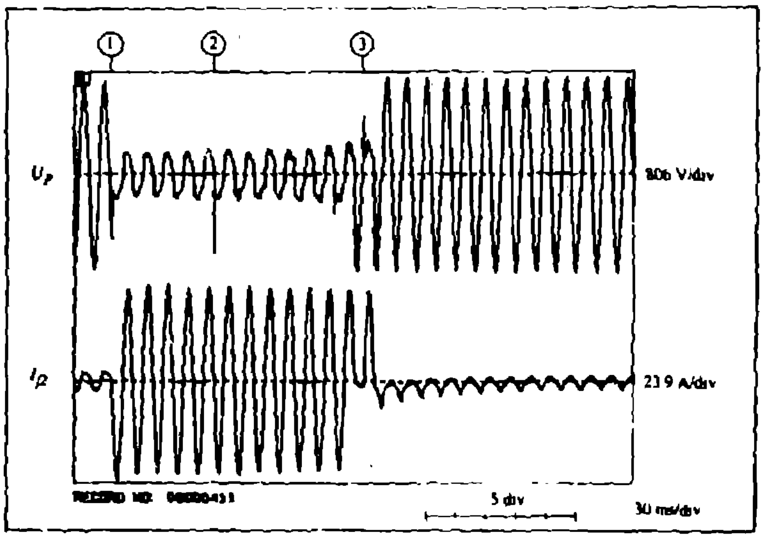


Figure 5.9 Voltage and current in test no.3.

number of turns involved in the short circuit. It seemed as if the noise increased by the number of short-circuited turns. The reason for this is that the transformer core became increasingly saturated as the number of short-circuited turns increased.

5.5.5 The fault evolution stops up

In some of the tests it seemed as if equilibrium occurred between the generated and dissipated heat. In test no.15, with 20% of the coil short-circuited, the coil was not damaged at all. The generation of bubbles was also low in this test. The main reason for the fault evolution to cease in this test was that the supply voltage decreased to a very low value, caused by the voltage drop in the supply system.

5.5.6 General observations during the tests

It is common for the course of events with short circuits between neighbouring turns and short circuits between layers that when the short circuit is placed inside the coil, the big gas bubbles seem to flow from the upper or lower part of the coil. This has also been observed in the literature [35]. The reason for this must be that it is easier for the gas bubbles to move parallel to the layer insulation than through the layer insulation.

It is also clear that the production of bubbles will depend on the applied voltage on the transformer. In tests with two coils in series (test arrangement 2 and 3 in Figure 5.5 on page 71), the applied voltage did not decrease as much as in the tests with only one coil (test arrangement 1), when many turns were involved in the short circuit. When the applied voltage is maintained,

the power evolved in the short-circuited turns is larger.

The gas evolution can obviously be violent when many turns are involved in the short circuit. Internal arcs in the coil entails large gas production. The arcs are established when a part of a coil, conducting a big current, is melting off. The current can pass through the arc until the current reach its zero passage, and the gas production caused by the arcs during these milliseconds may be violent.

Formation of carbon particles in the oil:

This was observed in the tests where also light flashes were observed. In test no.20, in which the coil was made without paper as layer insulation, the oil also turned black from carbon particles after the test. In this test light flashes were observed when the earth fault occurred. This indicates that it is not necessary to have paper insulation to create carbon particles. It is, however, impossible to conclude from the tests if it is melted copper, arcs, or a combination of these together with mineral oil which creates carbon particles in oil[1].

The extent of destruction of the coils:

With short circuit between neighbouring turns in layers inside the coil, large parts of the coils were destroyed. Turns melted, and in many cases the fault developed further into a short circuit of other parts of the coil. Typically, craters in the coils were created. It seems as if the melted copper tends to flow outwards in the coils.

In the tests with short circuits between neighbouring turns in the outermost layer, damage only occurred in the short-circuited turn and the insulation varnish on the neighbouring turns in the same layer.

In the tests with short circuits between layers in test arrangement 1 in Figure 5.5 on page 71 (with the exception of test no.15 with 20% of the coil short-circuited), the insulation varnish on the short-circuited turns was damaged. Damage of the insulation varnish on turns in neighbouring layers was also observed. No turns were welded or melted off in the tests with short circuits between layers in test arrangement 1.

Short circuits between layers in test arrangement 2 and 3 led to more heavy destructions of the coils. Turns were melted off and welded together. It was also observed that large forces between the short-circuited and the healthy part of the coils had been present.

1. This will be handled more in detail in section 6.2.

5.6 COMPARISON OF THE ENERGY INPUT AND THE DEVELOPMENT OF THE FAULT

5.6.1 Tests with short circuits between neighbouring turns

Energy input until the short-circuited turn in the outermost layer melted off:

As an approximation all energy input was generated in the short-circuited turn. In test 1, the energy input until the short-circuited turn melted off was calculated to be 39.8 kWs. The energy necessary to melt the winding by an adiabatic heating process is $W'_{melt, adiab} = 21.3\ kWs$. The energy generated in the short-circuited turn was $1.87 W'_{melt, adiab}$. This shows that the heating of the short-circuited turn situated in the outermost layer is not adiabatic. There is heat conduction to other parts of the coil both longitudinally of the short-circuited turn, and to turns beside and inside the short-circuited turn, along with heat conduction to the oil surrounding the turn.

Energy input until the short-circuited turn in layers inside the coil developed further:

The average value of the energy evolved in the transformers until the faults developed further for test no.3, 7, 8, 9, 10 and 11 was $W'_{mean} = 18.3\ kWs$. If the heating of the short-circuited turn was an adiabatic process, the temperature of the short-circuited turn when the fault developed further can be calculated from:

$$W' = m_{winding} q_{Cu} (T - 20) \quad [Ws] \tag{5.2}$$

With $m_{winding} = 0.051\ kg$ and $q_{Cu} = 393\ \frac{Ws}{kgK}$ it is found that $T = 933\ ^oC$. This temperature is lower than the melting temperature of copper. If the temperature was the same along the whole short-circuited turn, the fault would develop further until the short-circuited turn reached the melting temperature. If there has been inhomogeneities in the conductor or in its surroundings, it may have caused a local overheating in one or more places in the conductor, such that only parts of the conductor had reached the melting temperature when the fault developed further. See also section 5.9 and 5.10.1

5.6.2 Tests with short circuits between layers

Energy input until the short circuit between layers developed further:

The average value of the energy evolved in the transformers until the faults developed further for test no. 14, 17 and 18 was $W'_{average} = 384\ kWs$. If the heating of the short-circuited turns can be assumed to be an adiabatic process, the temperature in the short-circuited turns when the fault developed further can be calculated from equation (5.2), with $m_{winding} = 21 \cdot 0.051 = 1.071\ kg$. From this it is found that $T = 932\ ^oC$. See also section 5.10.2.

5.7 DEVELOPMENT OF THE TRANSFORMER EQUIVALENT CIRCUIT

It is desirable to develop equivalent circuits for the MV winding of the single-phase transformer

when N_S turns of the MV winding is short-circuited. The secondary LV winding is not included in the equivalent circuits. The T-equivalent of a single-phase transformer with a faulty MV coil is shown in Figure 5.10.

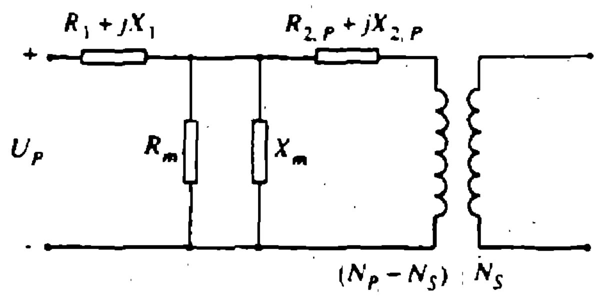


Figure 5.10 T-equivalent for a single-phase transformer.

It is desirable to move R_m and X_m to the left side of R_1 and X_1. If the core losses are neglected, it is given that $R_m = \infty$ and can be ignored from the equivalent circuit. If the winding resistances and the leakage reactances are combined, the equivalent circuit shown in Figure 5.11 is found.

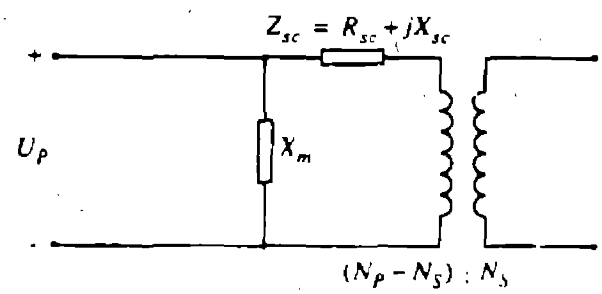


Figure 5.11 Simplified equivalent circuit for a single-phase transformer.

It is given that:

$$Z_{sc} = R_{sc} + jX_{sc} = \left(\frac{u_r + ju_x}{100}\right)\frac{U_N}{I_N} \tag{5.3}$$

where u_r is the ohmic component of the short circuit voltage in %, and u_x is the inductive component of the short circuit voltage in %.

In an ordinary distribution transformer u_x is around 4-5%, and u_r is around 1%. The short circuit current is then mainly determined by the leakage reactance X_{sc}. But in this case it is a short circuit

between turns in the primary coil. Then the short-circuited turns have the same cross section as the turns in the primary coil. Owing to this the short circuit resistance affects the short circuit impedance and the short circuit current more than in the case with a short-circuited secondary coil in the distribution transformer. The influence of the short circuit resistance will depend on the number of short-circuited turns.

The ohmic component of the short circuit voltage is given by

$$u_r = \frac{R_1 + R_{2,P}}{\dfrac{U_{N,P}}{I_{N,P}}} \cdot 100\% . \tag{5.4}$$

R_1 $= (N_P - N_S)\, R_{winding,\,20}$. The resistance of the primary coil at 20 °C.

R_2 $= N_S R_{winding,\,20}$. The resistance of the secondary coil at 20 °C.

$R_{2,P}$ $= R_2 n^2$.

The magnetizing reactance was found from measurements of applied voltage and current on no-loaded transformer. The measurements gave $U_P = 1840$ V and $I_P = 3.3$ A. From this it is found that

$$X_m = \frac{U_P}{I_P} = 558\ \Omega \tag{5.5}$$

5.7.1 Equivalent circuit with one turn short-circuited

Based on test arrangement 1 in Figure 5.5 on page 71, the following values are found:

$R_1 = 220 \cdot 0.002\ \Omega = 0.44\ \Omega$

$R_{2,P} = 0.002 \cdot 220^2\ \Omega = 96.8\ \Omega$

Combination with equation (5.4) gives

$u_r = 79.7\%$

If it is supposed that the inductive coupling between the short-circuited turn and the rest of the coil is in the same order as the inductive coupling between the medium- and low voltage coils in a distribution transformer (~4%), following approximations will be used:

$R_{sc} \gg X_{sc}$. X_{sc} is ignored in the equivalent circuit

$R_{2,P} \gg R_1$. R_1 is ignored in the equivalent circuit.

This gives the equivalent circuit shown in Figure 5.12

5.7.2 Equivalent circuit with 21 turns short-circuited

Based on test arrangement 1 in Figure 5.5 on page 71 the following values are found,

$R_1 = (220 - 21) \cdot 0.002\ \Omega = 0.4\ \Omega$

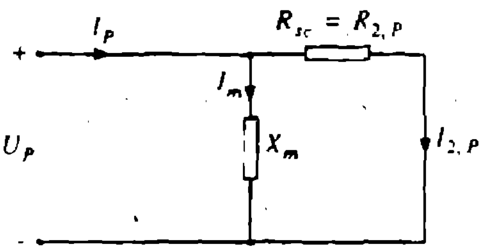


Figure 5.12 Equivalent circuit for the transformer with one turn short-circuited.

$$R_{2,P} = 21 \cdot 0.002 \cdot \left(\frac{(220-21)}{21}\right)^2 \ \Omega = 3.8 \ \Omega$$

Combination with equation (5.4) on page 83 gives

$$u_r = 3.45\%.$$

In this case X_{sc} can not be neglected. X_m can be neglected since $X_m \gg X_{sc}$. This gives the equivalent circuit shown in Figure 5.13.

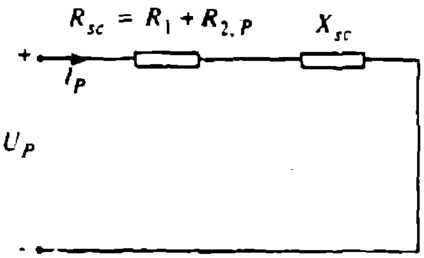


Figure 5.13 Equivalent circuit for the transformer with 21 turns short-circuited

In test no. 14 the voltage and current just after the voltage had been switched on was measured to be $U_P = 260 \ V$ and $I_P = 57 \ A$. This gives

$$Z_{sc} = \frac{U_P}{I_P} = 4.56 \ \Omega$$

$$X_{sc} = \sqrt{(Z_{sc}^2 - (R_1 + R_{2,P})^2)} = 1.8 \ \Omega$$

The equivalent circuit shown in Figure 5.13 is the same as described by equation (4.83) on page 56 in section 4.5.3. In the equivalent circuit for the transformer with only one turn short-circuited, magnetizing reactance is included because of the special design of the core.

5.8 THE CURRENT IN THE SHORT-CIRCUITED TURN

Measured value of I_S:

Measurements were done with one turn short-circuited in test arrangement 1 (see Figure 5.5 on page 71). The following values were measured:

$U_P = 100 \;\; V$ (applied voltage)

$I_P = 0.62 \;\; A$ (primary current)

$I_S = 139 \;\; A$ (current in the short-circuited turn)

The temperature in the short-circuited turn was measured to be 116 °C.

I_S calculated by using the equivalent circuit in Figure 5.12:

The resistance of the short-circuited turn at 20 °C is calculated to be

$$R_{winding,\,20} = 2.32 \;\; m\Omega$$

The resistance increases with the temperature as

$$R_{(T)} = R_{(20)}\,(1 + \alpha_{Cu}\,(T - 20)) \tag{5.6}$$

From equation (5.6) it is found that the resistance of the short-circuited turn at $T = 116 \;\; {}^oC$ is

$$R_{winding,\,116} = 3.20 \;\; m\Omega .$$

The current in the short-circuited turn referred to the primary side is

$$I_{2,\,P} = \frac{U_P}{n^2 R_{winding,\,116}} = \frac{100}{218.5^2 \cdot 3.2 \cdot 10^{-3}} = 0.66 \;\; A$$

The primary current is then calculated to be

$$I_P = \sqrt{I_{2,\,P}^2 + I_m^2} = \sqrt{I_{2,\,P}^2 + \left(\frac{U_P}{X_m}\right)^2} = \sqrt{0.66^2 + \left(\frac{100}{558}\right)^2} = 0.68 \;\; A$$

The current in the short-circuited turn is then calculated to be

$$I_S = nI_{2,\,P} = 218.5 \cdot 0.66 = 144 \;\; A .$$

The difference between the measured and calculated value of I_S from the equivalent circuit shown in Figure 5.12 is only 3.6%.

5.9 CALCULATION OF THE TEMPERATURE IN THE SHORT-CIRCUITED TURN

In the tests with one turn short-circuited, the fault developed further in two different ways:

1) The short-circuited turn melted off, and the transformer worked as normal

2) Other turns were involved in the short circuit.

In the following the temperature in the short-circuited turn will be calculated as a function of the time.

5.9.1 Assumptions

- The equivalent circuit in Figure 5.12 on page 84 is correct.
- All input energy is used to heat the short-circuited turn. The no-load losses were measured to be 0.38 kW, and will be neglected in the calculations.
- It is supposed that the heating of the short-circuited turn is an adiabatic process.
- It is supposed that the temperature coefficient of the electric resistance α_{Cu} is constant.
- It is supposed that the applied voltage is constant $U_P = 1.7 \ kV$. (In the measurements the voltage was about 1.4 kV just after the voltage was switched on, and it increased to 1.7 kV very fast.)
- The specific heat capacity for copper, (q_{Cu}), is supposed to be constant. (In [44] it is said to be constant between 1 and 100 °C).
- All the turns are supposed to have the same average length.

5.9.2 Development of the equation for the temperature in the short-circuited turn

The power in the short-circuited turn can be expressed as

$$P(t) = \frac{dW}{dt} = \frac{U_P^2}{R(t)} \tag{5.7}$$

The resistance can be expressed as

$$R(t) = R_{2,P,20}[1 + \alpha_{Cu}(T(t) - 20)] \tag{5.8}$$

Another relation is

$$dW = m_{winding} \ q_{Cu} \ dT$$

$$\frac{dT}{dW} = \frac{1}{m_{winding} \ q_{Cu}} \tag{5.9}$$

If equation (5.7) is multiplied with (5.9), it is found that

$$\frac{dW}{dt} \cdot \frac{dT}{dW} = \frac{1}{m_{winding} \cdot q_{Cu}} \cdot \frac{U_P^2}{R(t)} \tag{5.10}$$

If equation (5.8) is used in (5.10), it is found that

$$\frac{dT}{dt} = \frac{U_P^2}{m_{winding} \cdot q_{Cu} \cdot R_{2,P,20}} \cdot \frac{1}{1 + \alpha_{Cu}(T(t) - 20)} \tag{5.11}$$

Integration of equation (5.11) gives

$$\int (1 + \alpha_{Cu}[T(t) - 20]) \frac{dT}{dt} dt = \int \frac{U_P^2}{m_{winding} \cdot q_{Cu} \cdot R_{2,P,20}} dt \tag{5.12}$$

The solution of these indefinite integrals gives

$$\frac{1}{2}\alpha_{Cu}T^2 + (1 - 20\alpha_{Cu})T - \left[C + \frac{U_P^2 \cdot t}{m_{winding} \cdot q_{Cu} \cdot R_{2,P,20}}\right] = 0 \tag{5.13}$$

The solution of this quadratic equation is

$$T(t) = \frac{-(1 - 20\alpha_{Cu}) + \sqrt{(1 - 20\alpha_{Cu})^2 + 2\alpha_{Cu}\left[C + \frac{U_P^2 \cdot t}{m_{winding} \cdot q_{Cu} \cdot R_{2,P,20}}\right]}}{\alpha_{Cu}} \tag{5.14}$$

The constant C is found from the initial condition

$$T(0) = 20 \quad [^{\circ}C] \tag{5.15}$$

This gives that $C = 20 - 200\alpha_{Cu}$.
If this is used in equation (5.14), it is found that

$$\boxed{T(t) = \frac{-(1 - 20\alpha_{Cu}) + \sqrt{1 + \frac{2 \cdot U_P^2 \cdot \alpha_{Cu}}{m_{winding} \cdot q_{Cu} \cdot R_{2,P,20}}}}{\alpha_{Cu}}} \tag{5.16}$$

The transformer model has following parameters:

$U_P = 1700 \ V$

$m_{winding} = 0.051 \ kg$

$q_{Cu} = 393 \ \frac{J}{kg \cdot K}$

$R_{2,P,20} = 96.8 \ \Omega$

$\alpha_{Cu} = 0.00392 \ K^{-1}$

This gives the following equation for the temperature as a function of time for the short-circuited turn

$$\boxed{T(t) = \frac{-0.9216 + \sqrt{1 + 11.68 \cdot t}}{0.00392} \quad [^\circ C]} \tag{5.17}$$

The primary current is calculated as follows

$$\boxed{I_P(t) = \sqrt{\left(\frac{U_P}{X_m}\right)^2 + \left(\frac{U_P}{R(t)}\right)^2}} \tag{5.18}$$

The power in the short-circuited turn is calculated as

$$\boxed{P(t) = \frac{U_P^2}{R(t)}} \tag{5.19}$$

The results from the calculations are shown in Figure 5.14.

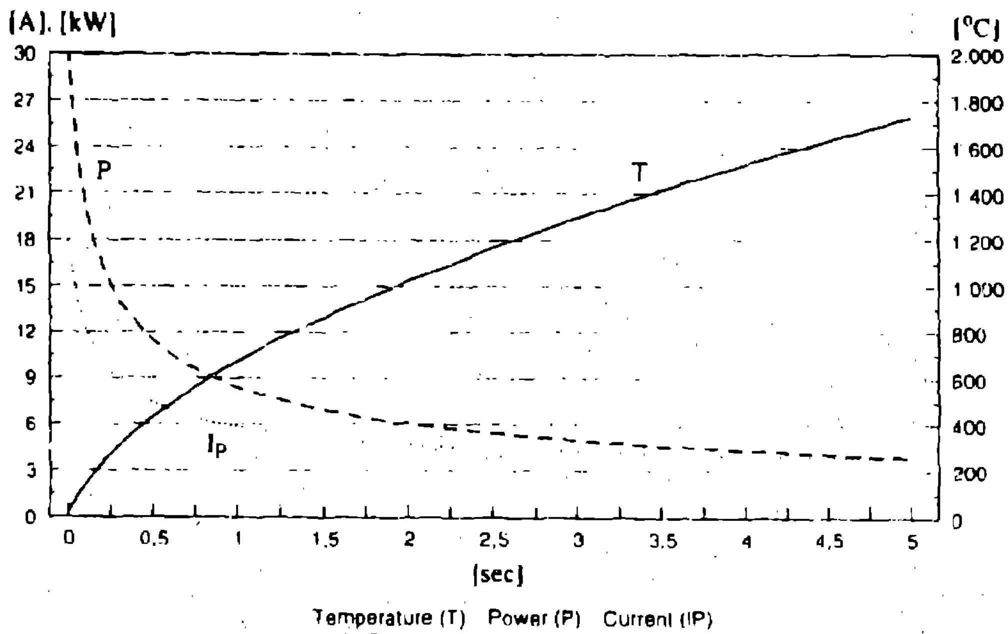


Figure 5.14 Calculated values of primary current, power and temperature in the short-circuited turn as a function of time

5.10 DETERMINATION OF THE TEMPERATURE BY HELP OF MEASUREMENTS AND CALCULATIONS

In the tests it was not feasible to measure the temperature in the short-circuited turns. In the following the temperature before further developing[1] of the fault will be calculated. For the calculations the equivalent circuits in Figure 5.12 on page 84 and Figure 5.13 on page 84 will be used, together with measured values for primary voltage, primary current and power input just before the fault develops further.

5.10.1 Tests with short circuits between neighbouring turns in the same layer

Assumptions:

- The equivalent circuit in Figure 5.12 on page 84 is correct.
- All input energy is used to heat the short-circuited turn (the no-load losses are neglected)
- α_{Cu} is supposed to be constant.
- All the turns have the same average length.
- The temperature in the turns not short-circuited is 20 °C.

The current in the short-circuited turn referred to the primary is given by

$$I_{2,P} = \sqrt{I_P^2 - I_m^2} = \sqrt{I_P^2 - \left(\frac{U_P}{X_m}\right)^2} \qquad (5.20)$$

The resistance in the short-circuited turn can be expressed in 3 ways:

$$R_{2,P,1} = \frac{P}{I_{2,P}^2} \qquad (5.21)$$

$$R_{2,P,2} = \frac{U_P}{I_{2,P}} \qquad (5.22)$$

$$R_{2,P,3} = \frac{U_P^2}{P} \qquad (5.23)$$

From equation (5.6) on page 85 it is found that the temperature in the short-circuited turn can be expressed as

$$T = \frac{\dfrac{R_{2,P,i}}{R_{2,P,20}} - 1}{\alpha_{Cu}} + 20 \quad [^\circ C] \qquad (5.24)$$

1. The short-circuited turn melted off, or other turns were involved in the short circuit.

The calculations are done for test no.1, 3, 7 and 9. The measured values for U_P, I_P and P are shown together with the calculated values for $I_{2,P}$, $R_{2,P,T}$ and T in Table 5.4.The melting temperature for copper is 1083 °C. The temperature in the short-circuited turn in test no.1 is calculated to be 355 °C higher than the melting temperature for copper. It is unlikely that the whole short-circuited turn has reached the melting temperature before it melted off. In test no.3, 7, 9 and 10 the temperatures calculated according to equation (5.24) are between 626 and 860 °C, with an average value of 721 °C.

From Figure 5.14 on page 88 it is found that 721 °C will be reached after about 1.1 sec. In the tests the time until the short circuits developed further was measured to be 1.36 - 1.9 sec. Some reasons for this difference may be:

- One of the approximations for the temperature curve in Figure 5.14 was that the heating of the short-circuited turn was an adiabatic process. This approximation differs from the reality.
- The applied voltage just after the voltage was switched on was about 1.4 kV, but in the development of the curves in Figure 5.14 the applied voltage was approximated to be constant $U_P = 1.7\ kV$.
- The temperature coefficient for copper (α_{Cu}) increases with temperature. Consequently the temperature will not increase as fast as shown in Figure 5.14.

5.10.2 Tests with short circuits between layers

Assumptions:

- The equivalent circuit in Figure 5.13 on page 84 is correct
- α_{Cu} is supposed to be constant.
- All the turns are supposed to have the same average length.

The calculations will be done for two different temperatures in the healthy turns,
1) The temperature of the healthy turns is 20 °C.
2) The temperature of the healthy turns is the same as in the short-circuited turns.

The leakage reactance for the transformer is calculated from measured values of primary voltage and current just after the voltage is turned on. It is assumed that the temperature in the short-circuited turns is 20 °C. The leakage reactance is calculated as

$$X_{sc} = \sqrt{Z_{sc}^2 - (R_{1,20} + R_{2,P,20})^2} \tag{5.25}$$

The resistance just before other turns are involved in the short circuit is calculated from measured values of primary voltage and current just before other turns are involved in the short circuit. The resistance is calculated as

$$R_{1,T} + R_{2,P,T} = \sqrt{Z_{sc}^2 - X_{sc}^2} \tag{5.26}$$

Fault development	The short-circuited turn melted off	Other turns were involved in the short circuit			
Test no.	1	3	7	9	10
U_P $[kV]$	1.8	1.8	1.8	1.7	3.65
I_P $[A]$	-	5.7	5.8	5.9	2.8
P $[kW]$	5.1	7.8	9.0	8.5	-
$I_{2,P}$ $[A]$	-	4.7	4.8	5.1	2.3
$R_{2,P,T} = \frac{P}{I_{2,P}^2}$ $[\Omega]$ (5.21)	-	353	391	327	-
$R_{2,P,T} = \frac{U_P}{I_{2,P}}$ $[\Omega]$ (5.22)	-	383	375	333	1569
$R_{2,P,T} = \frac{U_P^2}{P}$ $[\Omega]$ (5.23)	635	415	360	340	-
T $[^\circ C]$ ($R_{2,P,T}$ from (5.21))	-	695	795	626	-
T $[^\circ C]$ ($R_{2,P,T}$ from (5.22))	-	774	753	642	694
T $[^\circ C]$ ($R_{2,P,T}$ from (5.23))	1438	860	714	661	-

Table 5.4 Calculated values for resistance and temperature based on measurements of voltage, current and power.

The temperature in the short-circuited turns is then calculated from equation (5.24). The results from the measurements and calculations are shown in Table 5.5. From the calculations it is seen that the temperature of the healthy part of the coil has moderate influence on the temperature in the short-circuited turns. In test no.15 the short-circuited turns were not damaged at all. Therefore it is likely that the temperature has not been too high.

In the tests with 21 turns short-circuited it is seen that the average value of the temperature in the short-circuited turns is calculated to be 598 - 636 °C. If the heating of the short-circuited turns was to be an adiabatic process, the temperature was calculated to be 932 °C (see section 5.6.2). The time from the voltage was turned on until the fault developed further was many seconds, and then it is unlikely that the heating was an adiabatic process. Consequently it is more likely that the calculated temperature of 598 - 636 °C is in the correct range.

	Test arrangement 1		Test arrangement 3	
Test no.	14	15	17	18
U_P [V] (just after the voltage is turned on)	260	-80	1840	1850
I_P [A] (just after the voltage is turned on)	57	64	46.5	50
U_P [V] (just before the fault develops further)	660	-140	2790	2759
I_P [A] (just before the fault develops further)	51	63	35.3	37.2
P [kW] (at t = 32 s in test no.15)	-	9.9	-	-
X_{sc} [Ω] (calculated from equation (5.25))	1.84	-	34.4	31.3
$R_{2,P,20}$ [Ω]	3.77	1.32	18.77	18.77
$R_{2,P,T}$ [Ω]	12.4	2.14[a]	67.4	63.1
T [°C] (when the temperature in the healthy part of the coil is 20 °C)	604	180	681	622
T [°C] (when the temperature in the healthy part of the coil is the same as in the short-circuited part)	548	147	651	595

(a) The value of the resistance in test no.15 is calculated by help of the power P and the current I_P at T = 32 s

Table 5.5 Calculated values for reactance, resistance and temperature based on measured values of voltage and current (power in test no.15).

5.10.3 Comparison of the temperatures

From the calculations it is found that the temperature when a short circuit between neighbouring turns develops further is higher than in the tests with short circuits between layers. The reason for this may be as follows:

If only one turn is short-circuited, the cooling conditions and the temperature in the surroundings of the short-circuited turn are homogeneous. The temperature will be about the same along the short-circuited turn. Possible differences in the temperature will quickly be smoothed out because the length of the short-circuited turn is short, and the heat conduction longitudinal to the short-circuited turn is good. When many turns are involved in the short circuit, the turns will have different conditions with regard to cooling and temperature in the surroundings. Because of the length of the conductor, possible differences in the temperature lengthwise the conductor will not be smoothed out so fast. Then hot spots in the short-circuited turns may arise. Since the resistance increases by the temperature, the power evolution in the hot spots also increases. Then the fault

can develop further for a lower value of the average temperature in the short-circuited turns than in the case with only one turn short-circuited.

5.11 MEASUREMENTS ON THE MODEL TRANSFORMER WITH A LOW SUPPLY VOLTAGE

Some measurements were done with test arrangement 1 and 2 (see Figure 5.5 on page 71) with a low supply voltage. Following parameters were measured in the tests:

- The applied voltage U_P.
- The current I_P.
- The current in the short-circuited part of the coil I_S. Since the temperature in the short-circuited turns should be the same in all the tests, the measurements were done with $I_S = 50\ A$ in all the tests. In the calculations the temperature in the short-circuited turns was supposed to be about 20 °C.

The results from the measurements and calculations are shown in Table 5.6.

M.m.f. balance between the currents:

From the measurements it is seen that $n \approx I_S/I_P$. This means that m.m.f. balance between the currents exists. This is in agreement with the equivalent circuit in Figure 5.13 on page 84 in the cases with 21 or 46 turns short-circuited. In the tests with only one turn short-circuited, $I_P \approx I_{P,2}$ since $I_{2,P} \gg I_m$. This explains that there is m.m.f. balance also with only one turn short-circuited (see Figure 5.12 on page 84).

The values of the resistances:

In all the cases it is given that $R_1 \ll R_{2,P}$. This along with the fact that $n = (N_P - N_S)/N_S$ is almost doubled in the cases with two coils in series, leads to the fact that the value of R_{sc} is almost multiplied by four.

In the tests with only one turn short-circuited, it is seen that $Z_{sc} \neq R_{sc}$. The reason for this is that the resistance in the ammeter connected in series with the short-circuited turn, together with the contact resistance, is in the same order as the resistance in the short-circuited turn. In the cases with 21 and 46 turns short-circuited, the influence of these resistances can be ignored.

The values of the leakage reactances and the impedances:

It is seen that the short circuit impedance is increased with a factor 6 and 7.7 when 21 or 46 turns are short-circuited respectively, and the number of coils is increasing from one to two. Since R_{sc} is increasing with a factor 4.2 and 4.4, X_{sc} is increasing with a factor 9.1 and 19.2, respectively, for 21 and 46 turns short-circuited. In other words, the coupling between the short-circuited and the healthy turns is reduced drastically when the number of coils is increasing from one to two.

The value for X_{sc} is not calculated in the case with only one turn short-circuited, but in section

N_S	1		21		46	
Number of coils	1	2	1	2	1	2
$N_P - N_S$	220	440	199	419	174	394
$n = (N_P - N_S)/N_S$	220	440	9.48	19.95	3.78	8.57
U_P [V]	48.5	92	25.9	75.4	22.9	77.1
I_P [A]	0.24	0.12	5.2	2.5	12.8	5.6
I_S [A]	50	50	50	50	50	50
I_S/I_P	207	424	9.6	20	3.9	8.9
$Z_{sc} = U_P/I_P$ [Ω]	200	780	5.0	30.2	1.8	13.8
$(R_1 = (N_P - N_S) R_{winding,20})$ [Ω]	-	-	0.40	0.84	0.35	0.79
$(R_{2,P} = N_S R_{winding,20} n^2)$ [Ω]	96.8	387	3.8	16.7	1.32	6.75
$(R_{sc} = R_1 + R_{2,P})$ [Ω]	96.8	387	4.2	17.6	1.7	7.5
$X_{sc} = \sqrt{Z_{sc}^2 - R_{sc}^2}$ [Ω]	-	-	2.7	24.5	0.6	11.5
R_{sc} [p.u]	1.0	4.0	1.0	4.2	1.0	4.4
X_{sc} [p.u.]	-	-	1.0	9.1	1.0	19.2
Z_{sc} [p.u.]	1.0	3.9	1.0	6.0	1.0	7.7

Table 5.6 Measured and calculated parameters with low supply voltage on the model transformer

5.7.1 it was found that $X_{sc} \ll R_{sc}$.

5.11.1 Extrapolation of the results to full applied voltage

In the following the core saturation is ignored, and it is assumed a linear relation between applied voltage and currents. The results are shown in Table 5.6.

The p.u. value of the primary current:

It is seen that it can be difficult to detect a short circuit between two neighbouring turns, because the current is in the same order as the rated current for the transformer. From the calculations it is seen that in the cases with more than 4.8% of the winding short-circuited, the primary current becomes so large that it should be easily detectable.

It is also clear that as the value of the leakage reactance, (X_{sc}), depends of the position of the

N_S	1		21		46	
Number of coils	1	2	1	2	1	2
$\frac{N_S}{N_P} \cdot 100\%$	0.45	0.23	9.5	4.8	21	10.5
U_P $[kV]$	1.84	3.68	1.84	3.68	1.84	3.68
$I_{P,extr} = \frac{U_P}{Z_{sc}\|_{I_s = 50A}}$ $[A]$	(a) 19.0	(a) 9.51	368	122	1020	266
$I_{S,extr} = I_{P,extr} \cdot \left(\frac{I_S}{I_P}\right)\Big\|_{I_s = 50A}$ $[kA]$	3.94	4.03	3.53	2.44	4.00	2.37
$P_{winding} = R_{winding,20} \cdot I^2_{S,extr}$ $[kW]$	31.0	32.5	25.0	11.9	31.8	11.3
$\frac{I_{P,extr}}{I_{N,P}}$ [p.u.]	1.25	0.63	24.2	8.0	67.2	17.5
(a) With one turn short-circuited it was used that $Z_{sc} = R_{sc} = 96.8$ $[\Omega]$.						

Table 5.7 Extrapolated values from the measurements with low supply voltage.

short-circuited turns, there is no unique relation between the number of short-circuited turns and the value of the primary current.

The power loss in the short-circuited turns:

The power loss in each short-circuited turn, ($P_{winding}$), gives an indication of how fast the fault will develop further. The calculations show that $P_{winding}$ is less influenced by the total number of turns when only one turn is short-circuited. The reason for this is that the resistance in the short-circuited turn, referred to the primary side, determines the current. When the number of short-circuited turns is increasing, the leakage reactance, (X_{sc}), also matters. (See section 5.7).

5.12 LIMITATIONS IN THE MODEL TESTS

As mentioned in section 5.2, the basis for the model transformer was a three-phase, star/star connected, 315 kVA, 12/0.24 kV distribution transformer with four crossover coils in each medium voltage phase. It was desirable to simulate the conditions in the transformer mentioned above. Three essential distinctions between the model tests and the conditions for a three phase transformer situated in a normal distribution network were:

One- or two crossover coils instead of four:

In the model transformer either one or two crossover coils in series were used. The distribution transformer, being the basis for the model transformer, had four crossover coils in each phase. Because of this the development of a short circuit between layers in the model transformer involved a relatively larger part of the total number of turns compared to the full scale transformer.

The tests with a low supply voltage showed that the total number of turns is of importance for the primary current when the number of short-circuited turns was large. But the tests also showed that the current in the short-circuited turns was less influenced by the total number of turns when only one turn was short-circuited. The reason for this is that $X_{sc} \ll R_{sc}$, when the ratio between the number of healthy and short-circuited turns is large.

The applied voltage was not constant:

Because of a large short circuit impedance in the supply circuit in the model tests, the voltage drop in the supply circuit was very large when the number of short-circuited turns was large. This entailed a stop in the fault development. The short circuit impedance in a normal distribution network is so low that the applied voltage to the transformer is almost unaffected of the number of turns that is short-circuited.

Single-phase instead of three-phase transformer:

It is obvious that it is great differences between a single phase transformer and a star connected three phase transformer. This was shown in chapter 4.

5.13 Conclusions

The tests with short circuits between turns carried out on the model transformer gave new knowledge about the develo; mechanisms when turns are short-circuited in the MV winding of an oil-filled transformer. Some of the main results from the tests can be listed as follows:

- A short circuit between two neighbouring turns developed in three different directions:
  - the short-circuited turn melted off, and the current passed through the short circuit path.
  - the short-circuited turn melted off, but additional contact was established between two neighbouring turns, where the varnish was damaged by the high temperature in the short-circuited turn.
  - the fault developed further, and other turns were involved in the short circuit.
- When the short-circuited turn was situated in the outermost layer, gas bubbles were produced about 0.5 s. after the voltage was turned on. Then the quantity and size of the gas bubbles increased with time until the short-circuited turn melted off
- When the short circuit between two neighbouring turns was situated inside the coil, the faults developed further after 1.36-1.9 seconds. In these tests the gas bubbles started to flow

out from the coil about at the same time as the fault developed further.

- The fault development varied from one test arrangement to another (especially the time until the fault developed further).
- With the short circuit between turns situated in the layers inside the coil, large parts of the coils were destroyed. Turns melted, and in many cases the fault developed further so that other parts of the coils were short-circuited. Typically, craters were formed in the coils.
- It seems as if the melted copper tends to flow outwards in the coils.
- There were large axial forces between the short-circuited and the healthy part of the coils.
- In some of the tests it seemed as if equilibrium occurred with the heat produced being conducted away[1].
- The gas evolution can obviously be violent when many turns are involved in the short circuit.
- Internal arcs in the coil entail violent gas production.
- In some of the tests the oil became black from carbon particles, and in most of these tests light flashes were observed.
- The audible noise from the transformer increased with the number of short-circuited turns.

Electrical equivalent circuits for the model transformer is developed with validity for the situation with a few or many turns short-circuited. The main results from this work can be summarized as:

- The leakage reactance is decreasing very fast when the number of short-circuited turns is increasing. Since the resistance is also decreasing, this means that the line current is increasing very fast with the number of short-circuited turns.
- By help of a combination of the equivalent circuits and measurements on the transformer model, the average temperature in the short-circuited turns is calculated to be around 600-700 °C at the time when the fault develops further.

Measurements on the transformer model showed that the value of the leakage reactance depends on the position of the short-circuited turns, and there is no unique relation between the number of short-circuited turns and the value of the primary current.

1. The main reason for the fault evolution to stop was that the supply voltage decreased to a low value, caused by the voltage drop in the supply system

6 GENERATION OF GASES IN TRANSFORMERS

6.1 SUMMARY

In this chapter general theory about generation and composition of gases produced by faults in mineral-oil-filled transformers is described. Model tests in the laboratory, and interpretation of the gas analysis in accordance to existing rules are given.

Under normal operating conditions of oil-filled transformers hydrogen (H_2) is produced due to heat in addition to low-molecular hydro-carbon compounds, such as methane (CH_4). Carbon monoxide (CO) and carbon dioxide (CO_2) is generated by oxidation of cellulose [29], [45], [46].

The evolution of gas from a transformer is usually caused by a fault [7], [48]. Gases may also be formed due to natural ageing, but are formed to a much greater extent as a result of a fault [47]. When faults or abnormalities occur in the transformer, the quantities and chemical composition of the gases change. The rate of evolution of gas from the oil is proportional to the magnitude of the fault, although it will also give some indication of the type of fault; whilst the composition of gases is related to the type of fault, although this will change with magnitude of an individual fault [46].

The generation of gas in oil filled equipment by disruptive discharges (sparks and arcs) and severe overheating result from the chemical reactions which occur as a result of such faults. The evolved gas can be used to operate a relay so as to take the transformer out of service or to give an alarm signal. Analyses of free and dissolved gases are widely used as an effective maintenance method for power transformers. Another aspect of the gas evolution phenomenon is that the gases may be explosive in character. Serious accidents have been reported in the literature [48][1].

A large volume of gas is produced in a very short time from a normal type of arc. The gases produced with arcs in oil are mainly hydrogen (H_2) and acetylene (C_2H_2). If cellulose is present, carbon monoxide (CO) will also be produced. When there are partial discharges in oil, the gases produced are mainly hydrogen (H_2) and methane (CH_4). By local overheating of the oil, ethane (C_2H_6), ethylene (C_2H_4) and methane (CH_4) will be produced.

Experiments with gas production caused by hot (680-750 °C) copper conductors placed in transformer oil have been carried out on a test vessel in the laboratory. Tests were done both with and without paper insulation wrapped around the copper conductor. Both gas samples and oil samples from the tests have been analyzed. From the analysis of the gas samples it was found that in addition to ethane (C_2H_6), ethylene (C_2H_4) and methane (CH_4), the gas samples also included much hydrogen (H_2).

1 Another accident with a subsequent explosion of a substation caused by an internal fault in a distribution transformer is described in Appendix B

6.2 GASES GENERATED FROM OIL

In an oil insulated transformer, oil, either alone or as an impregnant, is in evidence practically everywhere that an internal fault can arise. Electrical discharges or thermal stresses in the oil or solid insulation, for example paper pressboard etc. of an oil filled transformer, cause degradation of these materials with the formation of gases of various types [13]. Under normal operating conditions, in addition to hydrogen (H_2) which is given off due to heat, also low-molecular hydrocarbon compounds (such as methane (CH_4)), plus carbon monoxide (CO) and carbon dioxide (CO_2), are given off by oxidation of the cellulose [29], [45], [46]. (See Table 6.1).

When faults or abnormalities occur in the transformer, the quantities and chemical composition of the gases change. Gases are generated by heat decomposition of oil or oil impregnated materials when faults due to local heating, partial discharge or arc discharge occur in the transformer. Higher temperatures and higher energies are caused by hot-spots or conductor overheating. With increasing temperature the proportion of unsaturated hydro-carbon compounds increases. If solid insulation materials are affected, the amount of carbon monoxide (CO) and carbon dioxide (CO_2) also increases [45], [49]. Partial discharges occur in case of fault of low-level energy (breakdown in gas-filled voids surrounded by oil- or oil-impregnated material). The main cause of decomposition in this case is ionic bombardment of the molecules and the major gas produced is hydrogen (H_2) [49]. High density electrical discharges break down the oil pyrolytically almost completely into its basic chemical components. In addition to carbon, which disperses evenly throughout the oil in the form of extremely fine particles, typical gases given off are hydrogen (H_2) and acetylene (C_2H_2) [45].

The rate of evolution of gas from insulating oil is proportional to the magnitude of the fault, although it will also give some indication of the type of fault; whilst the composition of the gases is related to the type of fault, although this will change with magnitude of an individual fault and with oil composition [46]. A large volume of gas is produced in a very short time from a normal type of arc [7], [33], [48]. A typical composition of gases with an arcing fault in transformer oil is 60-80% hydrogen (H_2), 20% acetylene (C_2H_2) and about 10% methane (CH_4). This mixture is flammable and explosive as well as non-condensable. Explosive effects are to be expected from the sudden pressure rise even when ignition of the gas does not take place [48]. The low dielectric strength and the non-condensable property of the gases can cause a relatively minor arc to become a major fault if the evolved gases envelop the major insulation, causing a breakdown of the line to ground insulation system [7].

Table 6.1 illustrates the gas composition which is experienced by normal transformers and by simulated faults. The results are based on a literature survey presented in [46].

Type of fault		H_2 [vol%]	CO [vol%]	CO_2 [vol%]	CH_4 [vol%]	C_2H_6 [vol%]	C_2H_4 [vol%]	C_2H_2 [vol%]
Arcing	Oil	57-74	0-1	0-3	0-3			14-24
	Oil+cellulose	41-53	13-24	1-2	1-10			14-21
	Oil+cellulose +resins	41-54	24-35	0-2	2-9			4-11
Partial discharge	Oil	50		5	45			
	Oil+cellulose	26	10.5	9.5	54			
Heating 200 °C	Oil+metal		2.4	9	11	0.5	0.1	
	Oil+metal +celulose		5	92	2	0.5		
Heating 350 °C	Oil+copper	4.7	0	74.5	10.2	8.8	0.8	0.1
	Oil+copper +cellulose	1.6	45.4	44.9	5.1	1.9	0.7	0.4
Normal service	1000 hours	2.8	13.8	77.2	2.8	1.7	1.7	
	10000 hours	1.2	9.6	84.3	3.1	1.0	0.8	

Table 6.1 Typical gas analyses for experimental and service conditions described in [46]

Generally, there are also mutual relations between the kind of faults and the gases generated [45], [50], [51]. See Table 6.2.

Kind of faults	Key gas for type of fault	Typical symptom gas (large proportion)	Typical symptom gas (small proportion)	Non-specific symptom gas
Arcing	H_2, C_2H_2	CH_4, C_2H_4	C_3H_6	C_2H_6, C_3H_8
Sparking	H_2, C_2H_2		CH_4, C_2H_4	C_2H_6, C_3H_6
Partial discharge	H_2		CH_4, C_2H_2	C_2H_6, C_2H_4
Local over heating >1000 °C	C_2H_4	CH_4	H_2, C_2H_2, C_3H_6	C_2H_6, C_3H_8

Table 6.2 Typical gas components for different kinds of faults in insulating oil for transformers.

Kind of faults	Key gas for type of fault	Typical symptom gas (large proportion)	Typical symptom gas (small proportion)	Non-specific symptom gas
Local overheating 300 - 1000 °C	C_2H_4	C_3H_6	CH_4	$H_2, C_2H_6, C_2H_2, C_3H_8$
Local overheating <300 °C	C_2H_6	C_3H_8	CH_4, C_2H_4	H_2, C_3H_6

Table 6.2 Typical gas components for different kinds of faults in insulating oil for transformers.

Methane (CH_4), ethylene (C_2H_4) and propylene (C_3H_6) are detected in significant amounts in the case of local heating. Hydrogen (H_2) and acetylene (C_2H_2) are detected in significant amounts for arc discharge.

The relative quantities of the gases vary in ways characteristic of how the energy available to decompose the oil is released at the fault and hence in ways characteristic of the type of fault.

Values for the explosive limits and ignition temperatures for some of the gases are shown in Table 6.3.

Chemical name	Chemical formula	Explosive limits [% by volume]	Ignition temperature [°C]
Hydrogen	H_2	4.1 - 75	530
Methane	CH_4	5.3 - 14	645
Acetylene	C_2H_2	2.5 - 80	335
Ethylene	C_2H_4	3.1 - 32	450
Ethane	C_2H_6	3.0 - 12.5	510
Propylene	C_3H_6	2.4 - 10.3	497
Propane	C_3H_8	2.2 - 9.5	466

Table 6.3 Values for the explosive limits and ignition temperatures for some gases [52]

The liquid degradation products which are formed, in addition to the flammable gases, lower the flash point and viscosity of the oil after prolonged serious faults [46].

6.3 CRITERIA FOR THE INTERPRETATION OF GASES IN TRANSFORMER OIL

The methods of interpretation described in the literature have been developed for power network transformers wound with copper conductors, insulated with cellulosic paper, pressboard-based

solid insulation and filled with hydrocarbon mineral oil.

Gas samples are taken from the gas relay after a fault in the transformer. Oil samples are obtained from the oil filled tank [13]. The sampling procedure should follow specified standards. The basic diagnosis is founded upon the types and relative quantities of gases generated by decomposition of oil under various fault conditions.

A convenient basis for fault diagnosis is the ratios of the concentrations of the gases present. The ratios used differ from one country to another, but the different methods described in the literature are principally based on IEC publication 599, [49]. One variant used in Germany with much success is briefly presented in Table 6.4. The table represents an assessment table for gas-in-oil analysis.

Ratios of characteristic gases	Code of range of ratios				
	$\frac{C_2H_2}{C_2H_6}$	$\frac{H_2}{CH_4}$	$\frac{C_2H_4}{C_2H_6}$	$\frac{C_2H_4}{C_3H_6}$	(1) $\frac{CO_2}{CO}$
< 0.3	0	0	0	0	1
0.3 - 1.0	1	0	0	1	1
1.0 - 3.0	1	1	1	2	1
3.0 - 10.0	2	2	1	3	0
> 10.0	2	3	1	3	2
Normal decomposition of insulants	0	0	0	0	0
Discharges with high energy	2	1	1	3	1
Discharges with low energy	2	2	1	3	1
Partial discharges with high energy density	1	3	0	+	0
Partial discharges with low energy density	0	3	0	+	0
Local overheating up to 300 °C	0	0	0	1	2
Local overheating from 300 to 1000 °C	0	0	1	2	2
Local overheating over 1000 °C	1	0	1	3	2

(1) Only valid with strong participation of cellulose
\+ Non-indicative

Table 6.4 Criteria for the interpretation of faults in transformer oil [45]

The method is mainly for diagnosis and maintenance for large transformers.

6.4 MODEL TESTS IN THE LABORATORY

It was desirable to examine the gases produced in the model tests described in chapter 5. But it was in practice difficult to make an arrangement for taking gas samples from the gases produced during the tests on the model transformer. Then it was decided to build a separate experimental arrangement for this purpose. It was desirable to study the gas production under corresponding requirements as in the tests with the model transformer. This was not possible in regard to the internal arcs in the coils. Then the tests were limited to study the gas production when the temperature of the Cu-conductor was as calculated for the tests on the model transformer (~600-800 °C).

6.4.1 Experimental arrangement for the sampling of gases and oil from the test vessel

Figure 6.1 shows the experimental arrangement used for the sampling of oil and gases from the test vessel.

About 10 dm^3 of old, filtered and dried transformer oil was filled into the test vessel[1]. The dotted line indicates the oil level in the tank

The sampling vessel for gas was a 500 ml glass bottle, and the sampling vessel for oil was a 180 ml glass bottle.

The electrodes A and B were connected to an adjustable high current transformer. Because of the heavy power loss in the bushings and in the Cu-conductor, pipes with cooling water were located inside the brass tank and around the bushings

A thermocouple was located at the mid-point of the Cu-conductor.

To see how the paper insulation affected the gas generation, tests with two different Cu-conductor arrangements were done:

Test 1: Pieces of porcelain pipes (1 cm long) were placed over the Cu-conductor. This was done because it was difficult to achieve a sufficient high temperature in the Cu-conductor without melting it.

Test 2: Insulating paper was wrapped around the Cu-conductor. This configuration was realistic with regard to the model tests on the single-phase transformer.

6.4.2 Sampling procedure

The apparatus was connected as shown in Figure 6.1. Before the sampling started, V1, V2, V4,

1 This oil is also used by a transformer manufacturer, and the same oil was used in the model tests described in chapter 5.

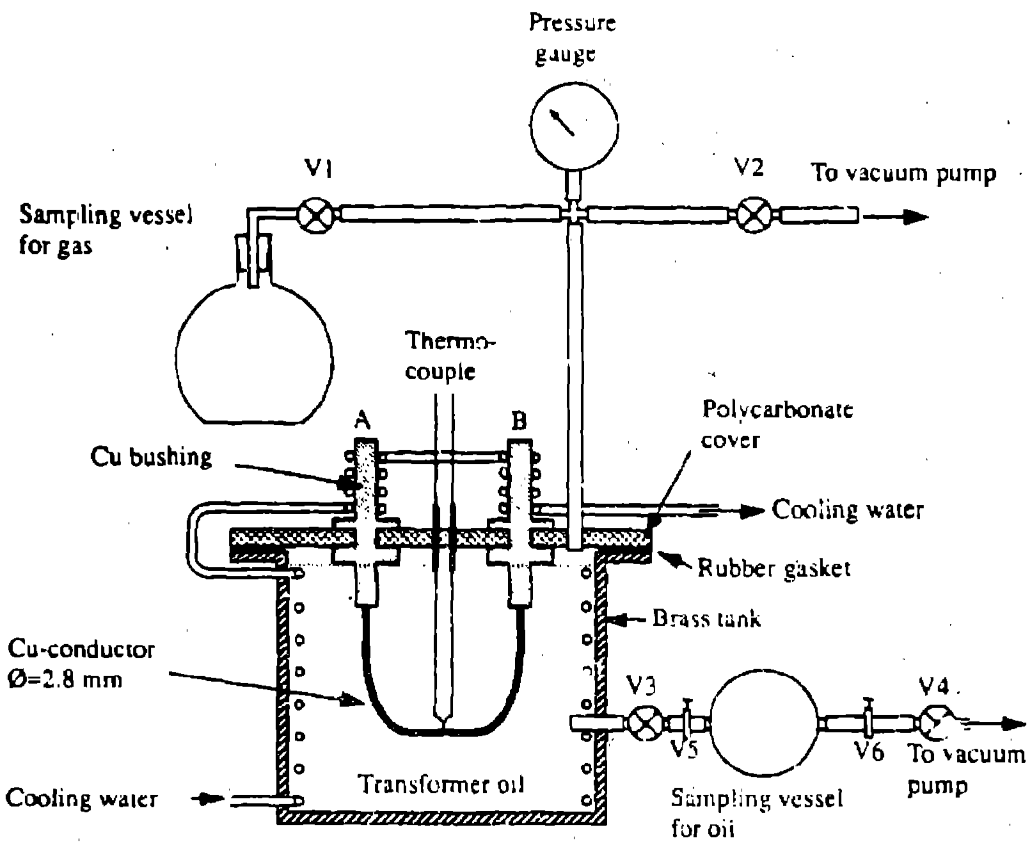


Figure 6.1 The experimental arrangement for the sampling of gases and oil from the test vessel.

V5 and V6 were opened, and the vacuum pump was started. During this process the system was evacuated. When this process was finished, V2, V4 and V6 were closed, and the vacuum pump was turned off. The cooling water and the high current transformer were turned on. The current was increased until the required temperature in the Cu-conductor was reached.

When the pressure had reached a required value, V1 was closed and the gas sampling was finished. V3 was carefully opened, and oil from the test vessel flowed into the sampling vessel for oil. When the sampling vessel was filled up, V3 and V5 were closed, and the oil sampling was finished.

The following parameters were controlled during the two tests:

Test 1: The total sampling time was 120 minutes. The rms value of the current was 460 A, and the temperature of the Cu-conductor was about 750 °C. The pressure was 420 mbar

when V1 was closed

- Test 2: The total sampling time was 50 minutes. The rms value of the current was 368 A, and the temperature in the Cu-conductor was about 680 °C. The pressure was 420 mbar when V1 was closed. A larger part of the Cu-conductor was red-hot in this test than in test 1, and the production rate of gases was higher. The production of grey vapour was high in this test.

6.4.3 Results from the gas analysis

The gas samples were analyzed at the Faculty of Chemistry and Chemical Technology at NTH, and the results are presented in Table 6.5.

Chemical formula	Chemical name	Test 1 [vol %]	Test 2 [vol.%]
H_2	Hydrogen	24.32	18.70
O_2	Oxygen	2.68	4.23
N_2	Nitrogen	7.00	9.14
CH_4	Methane	29.07	20.45
CO	Carbon monoxide	0.64	7.77
CO_2	Carbon dioxide	1.30	7.00
C_2H_4	Ethylene	28.36	25.77
C_2H_6	Ethane	3.71	3.18
C_3H_6	Propylene	2.48	3.25
C_3H_8	Propane	0.27	0.30
C_2H_2	Acetylene	0.03	0.04
N-C_4	N-butane	0.13	0.15
C_4		0.01	0.01

Table 6.5 Results from the analysis of the gas samples.

The oil samples were analyzed at Oslo Electricity Board, and the results are presented in Table 6.6. The oil analyzed in sample 3 was also old but filtered transformer oil, and the analysis was done just to have a reference for the two other tests.

If the results from the gas-in-oil analysis in Table 6.6 are analyzed with respect to the rules in Table 6.4 on page 102, test 1 and test 2 give right diagnosis. But the results from sample 3 (old,

Chemical formula	Chemical name	Test 1	Test 2	Sample 3
		[µl/l]	[µl/l]	[µl/l]
H_2	Hydrogen	1401	959	<0.5
O_2	Oxygen	4392	4565	12538
N_2	Nitrogen	10222	8561	31623
CH_4	Methane	20784	12290	7.1
CO	Carbon monoxide	<5.0	<5.0	<5.0
CO_2	Carbon dioxide	593	1231	172
C_2H_4	Ethylene	19136	17040	61.8
C_2H_6	Ethane	12232	10007	21.8
C_2H_2	Acetylene	<0.5	<0.5	<0.5
C_3H_8+C_3H_6	Propane + Propylene	14094	14255	168

Table 6.6 Results from the analysis of the oil samples

filtered oil) are not as expected; this is not surprising, since the previous history of the oil is not known.

6.4.4 Limitations in the tests

In these tests the gas production was only caused by the high temperature of the Cu-conductor. In the model tests with the single phase transformer described in chapter 5, the gas production was also caused by internal arcs in the coils. This was disregarded in the gas sampling tests.

The oil and the coils that were used in the transformer model were not evacuated for gas and moisture before the tests. This was done in the oil sampling tests.

The pressure on the surface of the oil was about 1 bar_{abs} in the tests on the transformer model and 0-0.42 bar_{abs} in the gas- and oil sampling tests. This difference in the pressures affects the formation of vapour

6.5 CONCLUSIONS

Gases are generated by heat decomposition of oil or oil impregnated materials when faults due to local heating, partial discharge or arc discharge occur in the transformer.

- With increasing temperature the proportions of unsaturated hydro-carbon compounds increase[1].
- If solid insulation materials are affected, the amount of carbon monoxide (CO) and carbon dioxide (CO_2) also increases.
- Partial discharges of low energy causes ionic bombardment of the molecules, and the major gas produced is hydrogen (H_2).
- High density electrical discharges break down the oil pyrolytically almost completely into its basic chemical components. In addition to carbon, which disperses evenly throughout the oil in form of extremely fine particles, hydrogen (H_2) and acetylene (C_2H_2) are typically produced.
- The rate of evolution of gas from insulating oil is proportional to the magnitude of the fault.
- The composition of the gases is related to the type of fault.
- A large volume of gas is produced in a very short time from a normal type of arc.

The gases and mixtures of gases are flammable and explosive as well as non-condensable. The explosion limits (in % by volume in air) for some of the gases are wide, and the ignition temperatures are relatively low.

The analysis of the gas samples from the experiments with the heated Cu-conductor in oil showed that the main gases produced during the experiments were hydrogen (H_2), methane (CH_4) and ethylene (C_2H_4). It was surprising that the amount of hydrogen (H_2) was so high with this kind of "fault".

1. Higher temperatures and higher energies are caused by hot-spots or conductor overheating.

7 FULL SCALE TESTS WITH SHORT CIRCUITS BETWEEN TURNS OR LAYERS IN THE MEDIUM VOLTAGE COIL

7.1 SUMMARY

The experiments with short circuits between turns on the single-phase transformer model described in chapter 5 formed the basis of corresponding full scale tests on three-phase transformers. Five full scale tests have been carried out with short circuits between neighbouring turns or layers in one MV winding on loaded, mineral-oil-filled, 11.43/0.23 kV, 300-315 kVA distribution transformers.

After a brief description of the test set-up and fault initiations, a rather detailed description of fault development in the 5 transformers under test is given. A brief summary of the development of important parameters during the tests is given at the end of the chapter.

The transformers were secondary loaded with ohmic resistances to about $0.5 \times S_N$. The primary line currents increased with 13-17% when only one MV turn was short-circuited. The tests showed that it is almost inconceivable to detect a short circuit between two neighbouring MV turns with an overcurrent protection relay.

The time from the short circuits between neighbouring turns were established until the faults developed further was measured to be 1.75-3.2 s. When an increasing number of turns were involved in the short circuit, the line currents increased quite fast. About 100 ms after the faults developed further, the line currents had increased to about $4.2 - 8.6 \times I_{N,peak}$ for the transformers. The maximum measured peak values of the primary line currents in the tests varied from $6.9 - 11.2 \times I_{N,peak}$ for the transformers. In the test on the Dyn11 connected transformer, the line currents became very high when the fault suddenly developed further so that a large part of the faulty MV winding was involved in the short circuit.

When a large part of the windings were involved in the short circuit, the core saturation increased. This lead to increased leakage flux in the transformer tank, and the temperature of the transformer tank increased.

In all the tests with short circuits between neighbouring turns, and where the fault developed further, gas bubbles were observed flowing out from the faulty windings. Large amounts of gases were produced in some of the tests. The gas actuated Buchholz-relays operated very satisfactorily both for the transformers equipped with conservator, and for the transformers of the hermetically-sea...

In 4 o... tests parts of the MV coils on the faulted limb were completely destroyed. Parts of the coils ...ed, and in some of the tests the mechanical destruction was considerable. The destructions seemed to be close up to what have been observed on faulty transformers removed from service.

7.2 EXPERIMENTAL ARRANGEMENTS FOR THE MEASUREMENTS

Because of the danger of explosion associated with this kind of faults it was decided that the experiments could not be carried out in the high voltage (and high current) laboratory at NTH/EFI. Trondheim Electricity Board was very positive and cooperative and they made available an *11.43 kV, 3x185 mm²* Al cable protected by a circuit breaker. The 3-phase short circuit current was 8.2 kA, and the 2-phase short circuit current was 7.1 kA. The area where the experiments were carried out is called "Munkvoll transformer station".

In this chapter the arrangements for the power supply, the measuring units and the short circuit arrangement in the transformers will be described.

7.2.1 Schematic description of the test arrangement

The tests arrangement is shown in Figure 7.1.

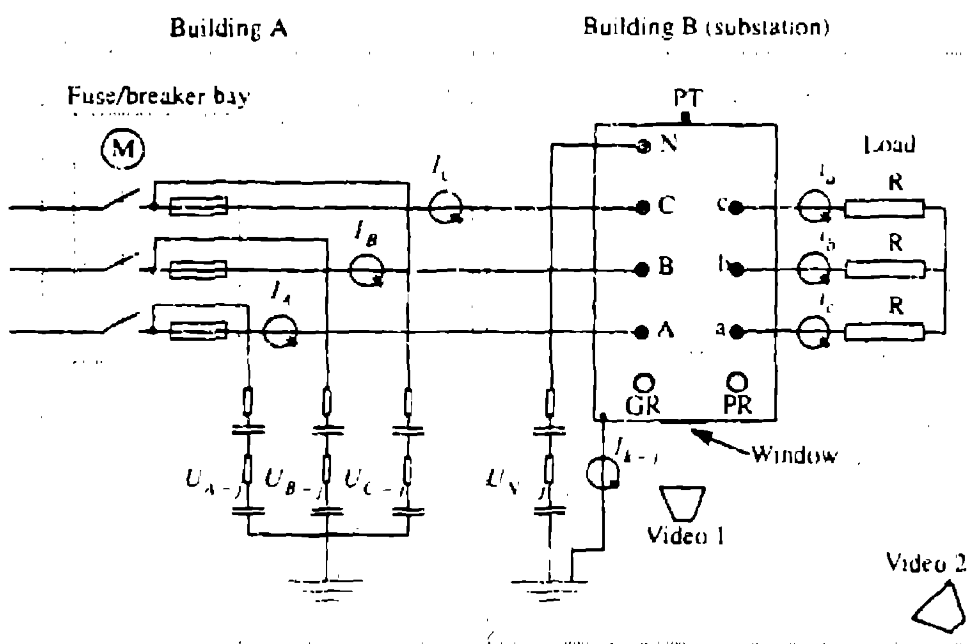


Figure 7.1 Schematic description of the test arrangement at "Munkvoll"

In Figure 7.1 it is necessary to give following list of abbreviations

PT	:	Pressure transmitter
GR	:	Gas actuated relay (Buchholz type)

PR : Pressure actuated relay
R : Load resistors

Current measurements:

The currents both on the medium voltage- and on the low voltage side of the transformer were measured with current transformers. It is well known that current transformers are not suited for measurements of DC-components of the currents. The use of LEM-modules with the capability of measuring DC components was prohibited due to the cost.

Voltage measurements:

The voltages were measured with damped capacitor dividers. In the cases where the test objects (the transformers) were YNy-connected the voltages between the respective phases and the neutral point (N) were measured directly with the differential connections on the transient recorder.

Load resistances:

To simulate a normal working condition for the transformers, a resistive load of about $0.5 \times I_N$ was designed. This resistances were made of stainless steel pipes. The outside diameters were 10 mm, and the wall thickness was 1 mm. To attain the required resistances the total pipe length in each resistance had to be 13.2 m. To get the resistances more easy to handle the pipes were wound as coils with diameter about 40 cm and about 11 turns. Each resistance was measured to be $R = 364\ m\Omega$. The power per phase was calculated to be about 50 kW. The inductance was measured to be only 28 µH and will be ignored.

The resistances were cooled by water, with a requirement of about 10 liter per minute per resistance. Because it was impossible to supply the demand of water from the ordinary water tap an arrangement with a water reservoir and a pump was established. See Figure 7.2.

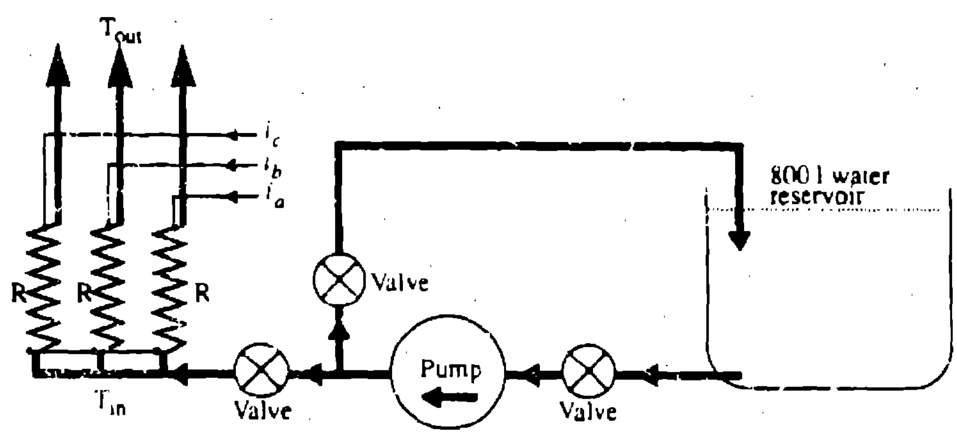


Figure 7.2 Schematic description of the cooling system for the load resistances

When the power in each phase was about 50 kW the temperature rise of the water was about $\Delta T = T_{out} - T_{in} = 70\ ^{\circ}C$.

Pressure transmitter:

This was a transmitter of the piezoresistive type with a measuring range from 0 to 6 bar_{abs}. The transmitter was installed on the drain cock in the lower part of the transformer tank.

Gas actuated relay:

These relays were of the Buchholz type. Two different types of relays were used depending on if the transformer was of the conservator type or of the hermetically-sealed type. Both types of relay will be briefly mentioned.

Conservator type:

During normal operation, the relay is completely filled with oil. When gas forms inside the transformer, the gas itself which tends to flow towards the conservator accumulates progressively inside the relay thereby lowering the oil level. The relay used in this tests was equipped with one float only. The amount of gas required to activate the alarm signal (GA) is 100 cm^3. When gas accumulation or oil leakage continues the release signal (GR) is activated. The disconnection signal will also be activated when the speed of the oil flow from the transformer to the conservator reaches 100 cm/sec.

Hermetically-sealed type:

This is a relay specifically designed for straight-on application to the transformer cover. The amount of gas required to activate the alarm signal (GA) is 120 cm^3. The disconnection signal will be activated if gas accumulation or oil leakage continues. For a better collection of the gas produced, the relay should be fitted in the uppermost position of the transformer.

Pressure actuated relay:

This relay operates when the pressure inside the transformer tank reach an adjusted value. This relay had two alarm terminals. Alarm 1 (PR) is set to operate when the overpressure reach 0.25 bar and alarm 2 is set to operate when the overpressure reach 0.30 bar. This pressure actuated relay was only used on the two transformers of the hermetically-sealed type.

7.2.2 Signal transmission, data sampling and data storage

Figure 7.3 gives a schematic description of the signal transmission system. The measuring instruments (voltage dividers, current transformers etc.) and the electrical to optical transmitters were placed in building A or B. The optical to electrical receivers, the transient recorders and the PC's were placed in the provisional control room. All signals were transmitted to the control room by optical fibers.

Three transient recorders and three PC's were used. The total number of available channels was

14. The maximum memory for each channel was 65kb. Since the memory was limited, and it was desirable to measure for a period up to 60 seconds, the sample frequency in three tests was as low as 1kHz.

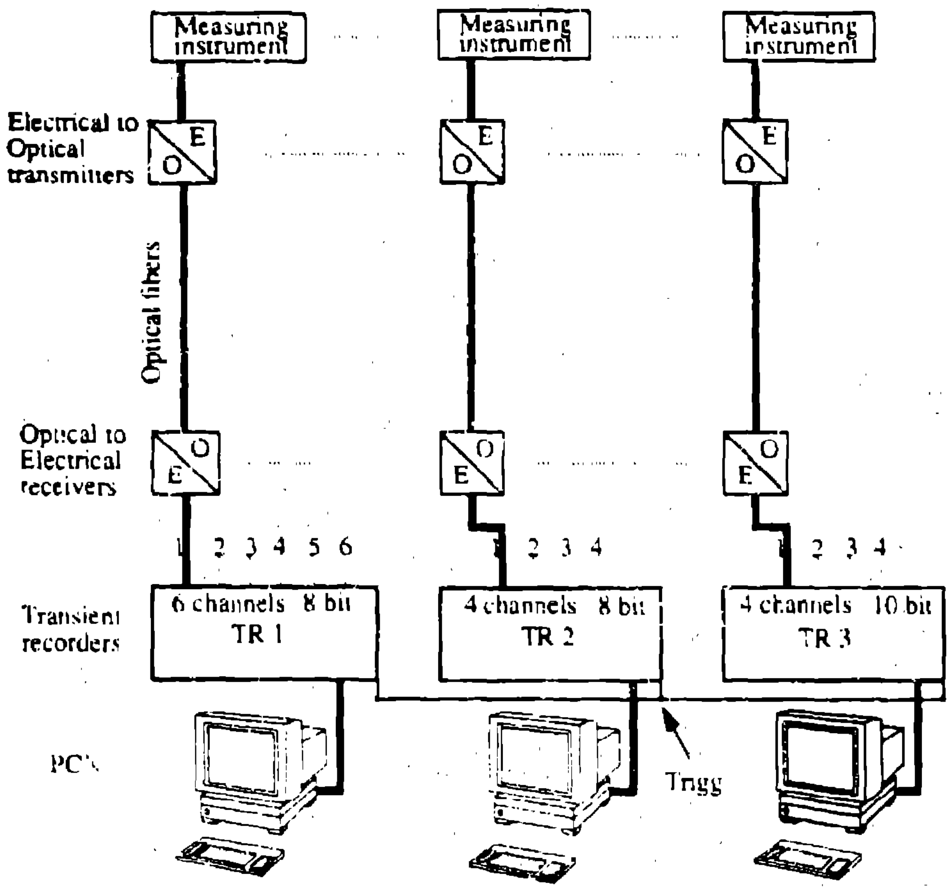


Figure 7.3 Schematic description of the signal transmission system

7.2.3 Description of the short circuit arrangement in the transformers

As shown in Figure 7.4 the short circuit between neighbouring turns or layers was established with a contactor (a relay) placed inside the transformer tank in the oil. The fundamental reason for establishing the short circuit by help of a contactor was to avoid the influence of the transformer inrush current. To the turns that were to be short-circuited copper conductors were solded, whose cross section was four times the cross section of conductors in the medium voltage coils. To get the inductance in the conductors to the contactor as low as possible the contactor was placed close to the coil connections.

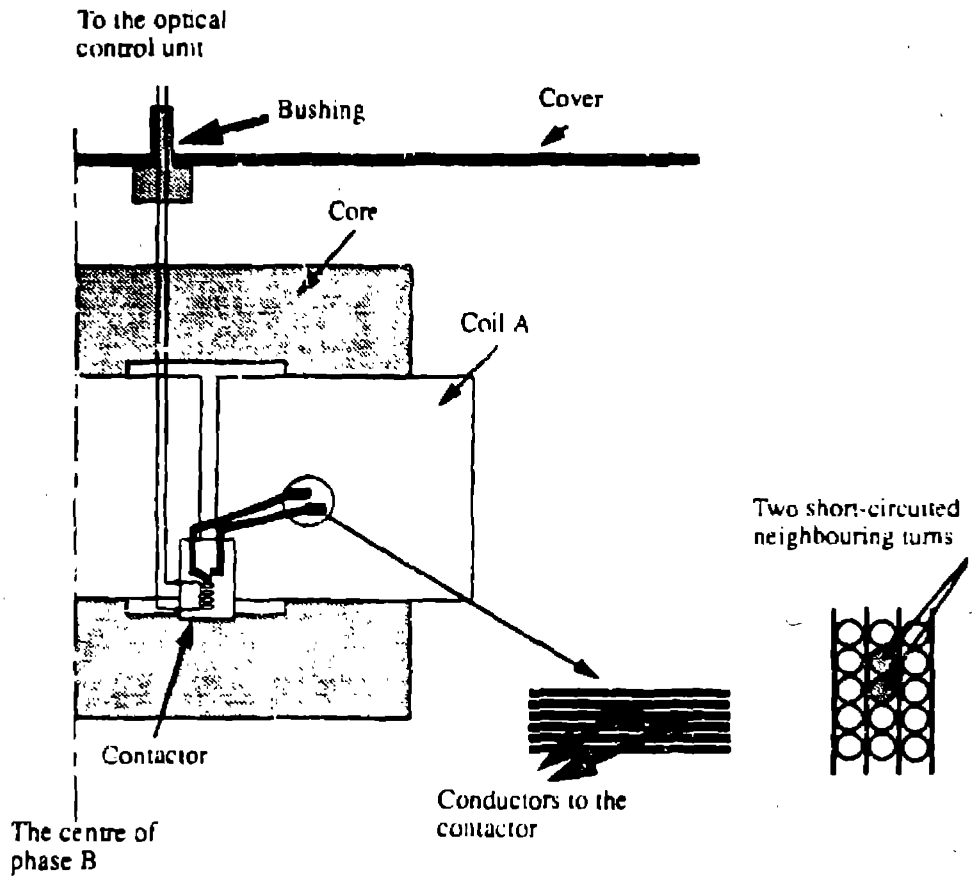


Figure 7.4 The short circuit arrangement in the transformer.

The short circuit was always situated in the coil placed on limb A. Since the potential of the contactor was on the same potential as the middle part of coil A (3.3 to 5.7 kV), also the electronic control components had to be at the same potential. Figure 7.5 shows the fundamental structure of the short circuit arrangement.

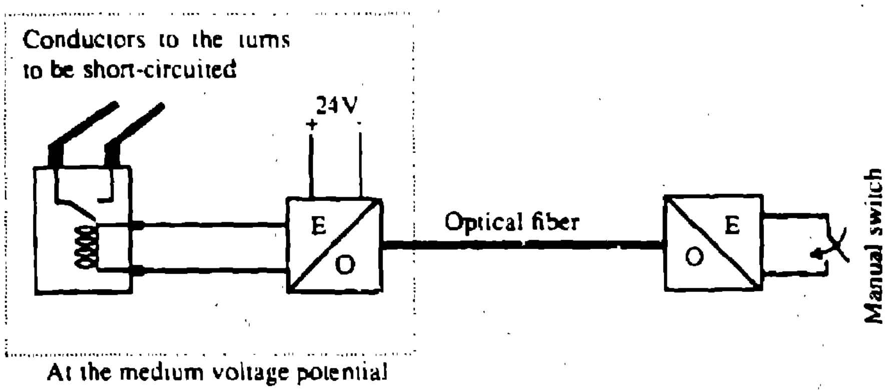


Figure 7.5 The fundamental structure of the short circuit arrangement.

7.3 A SURVEY OF TYPE OF TRANSFORMERS AND TYPE OF FAULTS THAT WERE TESTED

When the transformers were selected, it was desirable to study following parameters:

- type of short circuit (short circuit between neighbouring turns and between neighbouring layers)
- type of winding (crossover coil and coil of the layer type)
- type of transformer connection (YNy0 and Dyn11)
- type of transformer tank (conservator type and hermetically-sealed type)

Table 7.1 gives a survey of type of transformers and type of faults. It was of great interest to study how the terminal currents were influenced by the development of the fault in the medium voltage winding. It was also interesting to try to reconstruct faults in distribution transformers in ordinary operation. Another important question to answer was if a short circuit between neighbouring turns or layers could develop further to a short circuit between phases or to ground.

7.4 A DETAILED DESCRIPTION OF THE COURSE OF EVENTS IN EACH TEST

In the following a detailed description of the course of events for each transformer test will be given. Only a small selection of records from the measurements is presented.

Concerning the parameters, reference is made to Figure 7.1 on page 109. For transformer no 1, 2, 3, and 4 the voltages across each phase (between phase and neutral) will be called U_A, U_B and U_C.

	Connection	Type of winding	Rated Power [kVA]	Transformer tank	Type of fault	Fault in phase
Transf. no.1	YNy0	crossover coils	315	conservator	neighbouring turns	A
Transf. no.2	YNy0	layer coils	300	conservator	neighbouring layers	A
Transf. no.3	YNy0	layer coils	300	conservator	neighbouring turns	A
Transf. no.4	YNy0	layer coils	315	hermetically sealed	neighbouring turns	A
Transf. no.5	Dyn11	crossover coils	315	hermetically sealed	neighbouring turns	A-C

Table 7.1 Type of transformers and faults.

The presentation will include studies of the following parameters;

- currents in the medium voltage terminals[1]
- voltages between phases and neutral point in the medium voltage coils
- pressure in the transformer tank
- signals from the gas actuated Buchholz relay
- signals from the pressure actuated relay
- observations from the video recordings
- dissection of the transformer after the test

In the description the layers are numbered from the innermost layer

1 Also peak values are used because of the deviation from sinusoidal shape

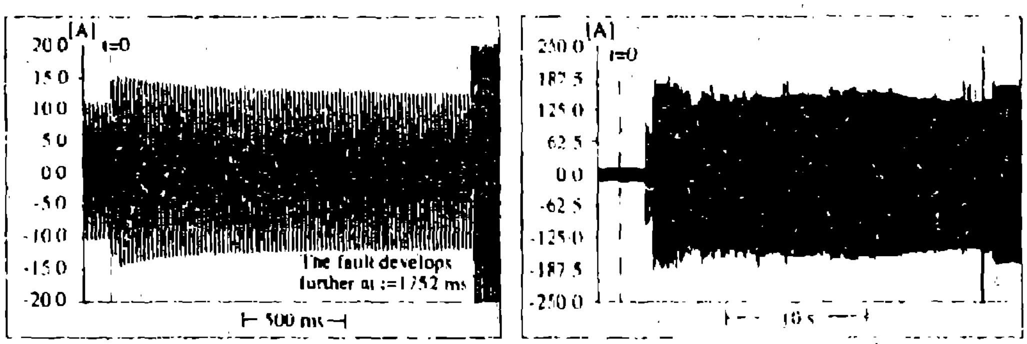
7.4.1 Test on transformer no.1. (YNy0, conservator type, neighbouring turns)

Key data for the transformer:

- Transformer number : 820171
- Transformer tank : Conservator type
- Connection : YNy0
- Type of windings : 4 crossover coils, numbered from the top to the bottom. Each crossover coil had 9 layers.
- Type of fault : Short circuit between two neighbouring turns in the middle of layer no.5 in coil no.2.

Currents in the medium voltage terminals:

Figure 7 6 shows the records from the current I_A for transformer no.1.



(a) (b)

Figure 7.6 The current I_A in transformer no.1.
(a) shows the current before the fault is developing further
(b) shows the current both before and after the fault developed further.

Stationary, and before the short circuit was established, the current in the phases is referred to as I_{F0}. During the three first electrical periods after the short circuit was established, the current in the phases is referred to as I_{F1}. Table 7 2 shows the results. The current in phase A is increased by 37%, and in phase B and C the increase is 10%.

At $t=1752$ *ms* the current in phase A is increasing to $I_{A,peak}=64$ *A*. At $t=1814$ *ms* the current is increasing once more to $I_{A,peak}=102$ A. From the Fourier transform of the current I_A it is seen that besides the fundamental frequency it includes 3^{rd}, 5^{th} and a small 7^{th} harmonics.

	$I_{F0,rms}$ [A]	$I_{F0,peak}$ [A]	$I_{F1,rms}$ [A]	$I_{F1,peak}$ [A]	$I_{F1,peak}/I_{F0,peak}$
Phase A	7.58	11.0	10.42	15.1	1.37
Phase B	7.51	10.55	8.19	11.65	1.10
Phase C	7.73	11.0	8.55	12.15	1.10

Table 7.2 Currents in the medium voltage terminals during the three first electrical periods after the short circuit was established.

At $t=2339$ *ms* the damaged part of the coil is increasing once more to $I_{A,peak}=150$-180 *A*. The ratio $I_{A,peak} / I_{N,peak}$ is now about 7.3.

26 seconds after the short circuit was established the peak value of the current I_A became more than 250 A for a short period.

Voltage between phases and neutral in the medium voltage coils:

Stationary and before the short circuit was established, the voltages between each phase and the neutral point were $U_{F0,rms}=6.50$ *kV* and $U_{F0,peak}= 9.46$ *kV*. Later the voltages were as shown in Table 7.3.

	$t=1752$ to $t=1814$ *ms* $U_{F,peak}$ [kV]	After $t=1814$ *ms* $U_{F,peak}$ [kV]	After $t=2339$ *ms* $U_{F,peak}$ [kV]
Phase A	7.92	6.48	4.56
Phase B	12.72	13.52	15.36
Phase C	10.64	10.80	12.32

Table 7.3 The voltages between phases and the neutral.

The increased voltages in the windings in phase B and C lead to increased magnetizing currents. This is shown in chapter 4.

Power flow in the transformer:

The increase in total power loss in the transformer in the period $t=0$ to $t=1752$ *ms* is $\Delta P_{loss,average} = 13.17$ *kW*. The total increase in energy loss is $\Delta W_{loss} = \Delta P_{loss,average} \cdot \Delta t = 23.08$ *kWs*.

Calculation of the energy needed (W_{melt}) to melt the short-circuited turn:

Conductor: $\varnothing = 3.15$ mm
$A = 7.79$ mm^2 (the cross section of the conductor)
$L = 0.94$ m (the length of one turn)

$$W_{melt} = m_{turn} \cdot q_{Cu} \cdot (T_{melt} - T_0)$$

$m_{turn} = \eta_{Cu} L \cdot A$
η_{Cu} = specific mass for copper = 8.93 [kg/dm^3]
q_{Cu} = specific heat capacity for copper = 393 [J/kgK]
T_{melt} = 1083 [°C]
T_0 = estimated temperature just before the short circuit is established = 20 [°C]

$W_{melt} = 0.065 \cdot 393 \cdot (1083 - 20) = 27.15$ [kWs]

From this it is seen that even if the short-circuited turn is heated adiabatically, the whole turn has not reached the melting temperature when the fault develops further inside the coil (when t=1752 ms). Probably inhomogenities in the conduction path or in its surroundings (sealing or paper-insulation) have caused a local overheating in one or more places in the conductor.

In the period $t=1752$ ms to $t=2339$ ms the calculated increase in power input in phase A and C compared to the average input power in phase A and C before the short circuit is established is $\Delta P_{A,average}$ = 132 kW and $\Delta P_{C,average}$ = 101 kW. In this period there is no complete measurement of the current I_B, and ΔP_B can not be calculated. The total power output of the transformer is about the same in this period as before the short circuit is established. The total power loss in the transformer is consequently more than 233 kW in this period.

Pressure in the transformer tank:

In Figure 7.7 the pressure together with the current I_A and the voltage U_A is shown

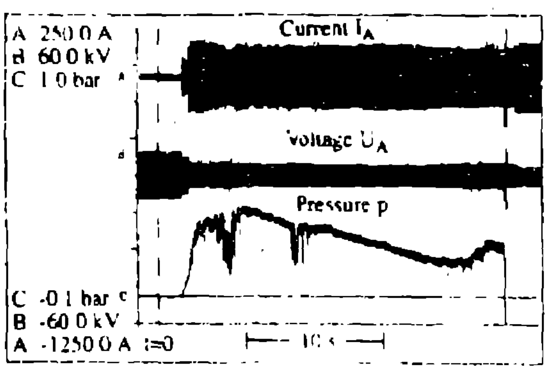


Figure 7.7 Current I_A, voltage U_A and pressure p for transformer no.1.

The pressure starts to increase at $t=1752$ ms. At $t=2339$ ms the pressure has reached 90 mbar. The

average pressure rise in this period is dp/dt = 0.15 mbar/ms. In the period $t=2339$ *ms* to $t=2764$ *ms* the average pressure rise is $dp/dt = 0.30$ *mbar/ms*.

The maximum pressure is reached at $t=6470$ *ms* and was measured to be $p_{max} = 320$ *mbar*.

Signals from the gas actuated Buchholz relay:

The alarm signal (GA) was actuated at $t=2273$ *ms*, i.e. 521 ms after the pressure started to increase. At this time the pressure was $p_{GA}=79$ *mbar*.

The release signal (GR) was actuated at $t=2350$ *ms*. The pressure was then $p_{GR}=100$ *mbar*.

Observations from the video recordings:

Gas bubbles were observed about two seconds after the short circuit was established. At the same time the noise from the transformer was increasing. The first gas bubbles were observed at the uppermost part of coil no.2. After a little while bubbles were also coming out of the lower part of coil no.2.

At $t=5$ *sec* the transformer oil became black, and 4-5 sec later a glimpse of light was observed. This may be caused by glowing, melted copper or from arcs in the coil.

26 sec after the short circuit was established (at the same time as $I_{A\,peak}$ became more than 250 A) an intense light flash and a crack was heard in the transformer. This was followed by black oil and large volume of gases. Gas also developed in coil no.3.

Through the inspection window in the conservator, gas bubbles in the oil were observed about 2.5 sec after the short circuit was established. Grey vapour above the oil level in the conservator was also observed.

Dissection of the transformer after the test:

Coil no.1 in phase A was not damaged, apart from some black insulation paper at the lower part of the coil. Figure 7.8 shows coil no.2 in phase A where the short circuit was established. The coil is completely damaged. At the place where the intense light flashes was observed, the coil is completely burned-out.

In coil no.3 in phase A almost the whole coil was either short-circuited or turns had melted.

Figure 7.8 Coil no.2 in phase A after the test on transformer no.1.

7.4.2 Test on transformer no.2. (YNy0, conservator type, neighbouring layers)

Key data for the transformer:

- Transformer number : 710090
- Transformer tank : Conservator type
- Connection : YNy0
- Type of windings : Layer type. Each MV winding had 7 layers.
- Type of fault : Short circuit between two neighbouring layers (layer no.3 and no.4)

Currents in the medium voltage terminals:

Due to malfunction of the current measurement in phase A I_A is calculated as $I_A = -(I_B + I_C)$.

Stationary, and before the short circuit was established the current in each phase is about $I_{F0,rms}=7.5$ A and $I_{F0,peak}=10.6$ A.

5 sec after the short circuit was established the current I_{F1} in the phases has the values shown in Table 7.4. From the analysis of currents it was observed that the current in phase B includes more of the 3rd and 5th harmonics than the currents in the two other phases.

The voltage was switched off 4 min 58 sec after the short circuit was established.

	$I_{F0,peak}$ [A]	$I_{F1,peak}$ [A]	$I_{F1,peak}/I_{F0,peak}$	$I_{F1,peak}/I_{N,peak}$
Phase A	10.6	61	5.75	2.85
Phase B	10.6	37	3.49	1.73
Phase C	10.6	34	3.20	1.59

Table 7.4 Currents in the medium voltage terminals 5 sec after the short circuit is established

Second test:
2 min 21 sec later the voltage was turned on again. The currents are as shown in Table 7.5.

	$I_{F2,peak}$ [A]	$I_{F2,peak}/I_{F0,peak}$	$I_{F2,peak}/I_{N,peak}$
Phase A	208	19.6	9.7
Phase B	161	15.2	7.5
Phase C	147	13.9	6.9

Table 7.5 Currents in the medium voltage terminals in the second test

Now the currents I_B and I_C includes more 3[rd] harmonics than earlier. I_A contains mainly the fundamental frequency

29 sec after the voltage was turned on again, the fuses in phase A and C operated and the load breaker opened.

Voltage between phases and neutral in the medium voltage coils:

The voltages are measured to be as shown in Table 7.6.

Pressure in the transformer tank:

No pressure rise was measured in the tank.

Signals from the gas actuated Buchholz relay:

The signals were not actuated during the first 29 sec after the short circuit was established. It is likely that the signals were actuated a short time after the large gas bubbles were observed, i.e. 40 sec after the short circuit was established.

	Before short circuiting $U_{F0\,peak}$ [kV]	After 5 sec $U_{F1\,peak}$ [kV]	Second test $U_{F2\,peak}$ [kV]
Phase A	9.52	6.32	0.64
Phase B	9.20	13.04	15.84
Phase C	9.44	12.16	15.60

Table 7.6 The voltages between phases and the neutral

Observations from the video recordings:

First test:
40 sec after the short circuit was established the noise became more intense, and large gas bubbles flowed out from the coil. It is also observed that hot oil flowed upwards from the lower part of coil A.

The temperature of the transformer tank must have been high (higher than 150 °C) since parts of the polycarbonate window started to melt under the metal flange. It is supposed that the high temperature of the transformer tank was caused by increased leakage flux in the tank. The increased leakage flux is again caused by increased core saturation when a large part of the windings are is included in the short circuit.

Second test:
29 sec after connection a crack was heard.

Dissection of the transformer after the test:

Phase A:
The insulation varnish on the turns and the layer insulation both inside and outside the two short-circuited layers were carbonized. In the short-circuited part of the coil, and in all the layers inside, some turns were melted off.

Phase B:
The turns have suffered from large mechanical movements. The lower part of the coil was moved towards the yoke insulation. The individual movements of the turns have caused internal short circuits in the coil, and some turns were almost melted off. See Figure 7.9.

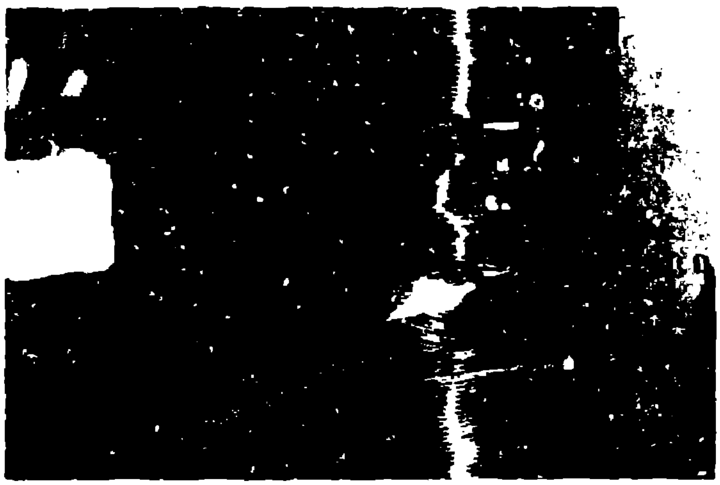


Figure 7.9 The MV winding on limb B. The turns have been exposed to large mechanical forces.

7.4.3 Test on transformer no.3. (YNy0, conservator type, neighbouring turns)

Key data for the transformer:

- Transformer number : 12124 (1969)
- Transformer tank : Conservator type
- Connection : YNy0
- Type of windings : Layer type. Each MV winding had 7 layers.
- Type of fault : Short circuit between two neighbouring turns in the middle of layer no.3

Currents in the medium voltage terminals:

Stationary, and before the short circuit was established the current in phase A is measured to be $I_{A0,rms}=7.52\ A$ and $I_{A0,peak}=10.55\ A$. During the three first electrical periods after the short circuit was established the current is; $I_{A1,rms}=8.97\ A$ and $I_{A1,peak}=12.65\ A$. The ratio $I_{A1,peak}/I_{A0,peak}=1.20$.

At $t=1712\ ms$ the fault develops further inside coil A, but the current is only increasing to $I_{A2,peak}=13.55\ A$. At $t=1990\ ms$ it seems as if the short circuit disappears. The fault seems to be intermittent. Figure 7.10 shows the record form I_A

In the periods when the short circuit disappears, the current flow in the coil may have been

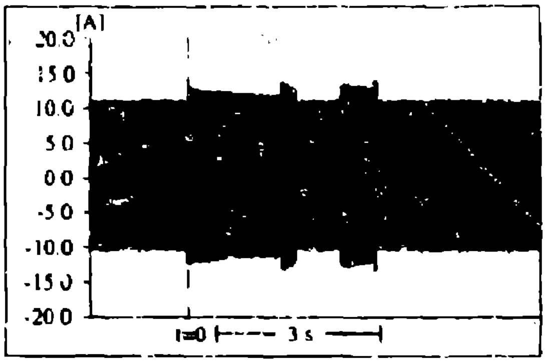


Figure 7.10 I_A in the test on transformer no.3.

through the contactor. Another possibility is that the melted off short-circuited turn established one or more contact points with adjacent neighbouring turns. This phenomena was also observed once in the model tests.

Pressure in the transformer tank:

No pressure rise inside the transformer tank was observed in this test.

Signals from the gas actuated Buchholz relay:

The alarm -and release signals were not actuated.

Observations from the video recordings:

No interruption of the service was observed on the video recordings.

Dissection of the transformer after the test:

The only destruction found was that the short-circuited turn was melted off, and the insulation varnish was carbonized. Some insulation varnish on the two neighbouring turns was also carbonized. It is possible that the current has been conducted through these ashes after the short-circuited turn melted off.

7.4.4 Test on transformer no.4. (YNy0, hermetically sealed, neighbouring turns)

Key data for the transformer:

- Transformer number : 940031
- Transformer tank : Hermetically sealed
- Connection : YNy0
- Type of windings : Layer type. Each MV winding had 9 layers.
- Type of fault : Short circuit between two neighbouring turns in the middle of layer no.5

Currents in the medium voltage terminals:

Figure 7.11 shows the records from the current I_A, I_B, and I_C for transformer no.4. Stationary and before the short circuit was established the current in the phases is called I_{F0}. During the three first electrical periods after the short circuit was established, the currents is called I_{F1}. The values for the current I_A after *t=3206 ms* (when the fault is developing further) is calculated as $I_A = -(I_B + I_C)$. See Table 7.7.

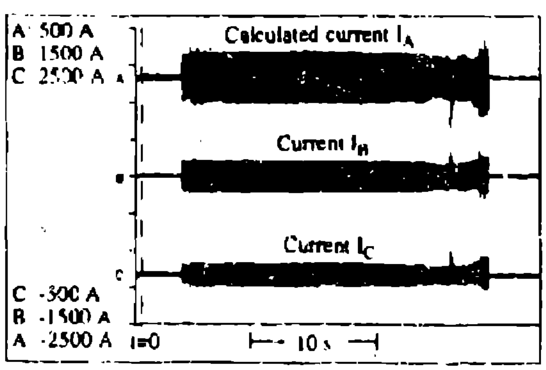


Figure 7.11 The records of the currents in the medium voltage terminals.

At *t=28099 ms* the current I_A is reduced to a very small value near zero (it is likely that a break in the conductor in the coil has occurred). At the same time the currents $|I_{B4,peak}| = |I_{C4,peak}| = 10.5$ *A* ($I_B = -I_C$ since $I_A = 0$)

At *t=35390 ms* the currents get the values; $I_{A5,peak}$*=252 A*, $I_{B5,peak}$*=178 A* and $I_{C5,peak}$*=98 A*. 50 ms later the currents became the same as at *t=28099 ms* again.

	$I_{F0,peak}$ [A]	$I_{F1,peak}$ [A]	$I_{F1,peak}/I_{F0,peak}$	$t=3206$ ms $I_{F2,peak}$ [A]	$I_{F2,peak}/I_{N,peak}$	$t=3266$ ms $I_{F3,peak}$ [A]	$I_{F3,peak}/I_{N,peak}$
Phase A	11.2	13.7	1.22	118	5.25	211	9.38
Phase B	-	-	-	76	3.38	140	6.22
Phase C	-	-	-	49	2.17	89	3.95

Table 7.7 Currents in the medium voltage terminals.

Voltage between phases and neutral in the medium voltage coils:

The voltages between the phases and the neutral are shown in Figure 7.12. The voltages are

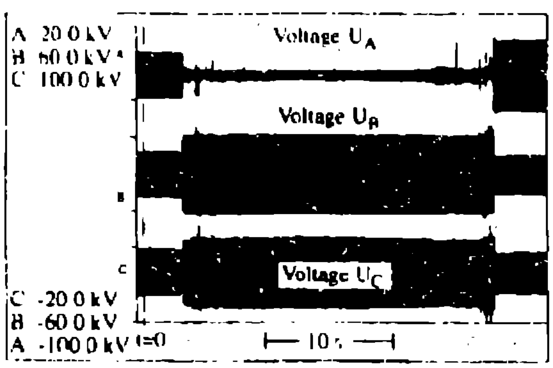


Figure 7.12 The records of the voltages between the phases and neutral for transformer no 4

measured to be as shown in Table 7.8

Pressure in the transformer tank:

The pressure started to rise at $t=3206$ *ms*. The maximum pressure was reached at $t=12723$ *ms* and was measured to be $p_{max}=420$ *mbar*. The average pressure rise in this period was $dp/dt=0.044$ *mbar/ms*.

Signal from the gas actuated Buchholz relay:

The alarm signal (GA) was actuated at $t=5442$ *ms*, i.e. 2236 ms after the fault developed further in coil A. The pressure when (GA) was actuated was $p_{GA}=150$ *mbar*.

	Before short circuiting $U_{F0,peak}$ [kV]	$t=12$ *sec* $U_{F1,peak}$ [kV]	$t=32$ *sec* $U_{F2,peak}$ [kV]
Phase A	9.1	1.8	14.5
Phase B	9.1	16.0	8.1
Phase C	9.1	14.5	8.2

Table 7.8 The voltages between phases and the neutral.

Signal from the pressure actuated relay:

The signal from the "Alarm 1 - terminals" on the pressure actuated relay (PR) was actuated at $t=6813$ *ms*, i.e. 3607 ms after the fault developed further in coil A. The pressure when (PR) was actuated was $p_{PR}=230$ *mbar*.

Observations from the video recordings:

3.2 sec after the short circuit was established the noise became more intense, and it could be heard that gas bubbles were produced. One sec. later a light flash was observed, and 3 sec after this the oil became black. It was not possible to see what was happening with the coil through the black oil.

At $t=28.1$ *sec* the fault seemed to disappear, and 7.3 sec later a crack was heard.

During the test grey vapour escaped under the transformer cover.

Dissection of the transformer after the test:

Only phase A was destroyed. It is observed that parts of the coil were melted off, and craters were observed some places on the coil.

Inside the coil, melted copper had established "canals". The melted copper had flowed out of the coil, and was distributed around inside the transformer tank. Turns in the layers both inside and outside the short-circuited turn were destroyed. See Figure 7.13.

Figure 7.13 The MV winding on limb A for transformer no.4. Four of the outermost layers are removed on this picture.

7.4.5 Test on transformer no.5. (Dyn11, hermetically sealed, neighbouring turns)

Key data for the transformer:

- Transformer number : 920886
- Transformer tank : Hermetically sealed
- Connection : Dyn11
- Type of windings : 4 crossover coils, numbered from the top to the bottom. Each crossover coil had 11 layers.
- Type of fault : Short circuit between two neighbouring turns in the middle of layer no 6 in coil no.2

Currents in the medium voltage terminals:

Figure 7.14 shows the records of the currents I_A, I_B, and I_C for transformer no.5. Stationary, and before the short circuit was established the current in the phases is referred to as I_{F0}. During the three first electrical periods after the short circuit was established, the current in the phases is

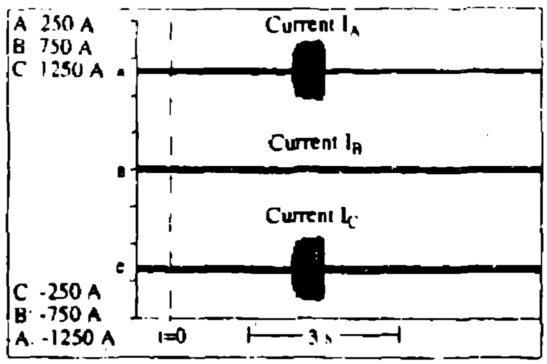


Figure 7.14 The records of the currents in the medium voltage terminals.

referred to as I_{F1}. The fault is developing further at $t=2432$ *ms*. During the next 5-6 electrical periods the currents are increasing to I_{F2}. At $t=3111$ *ms* the currents are suddenly decreasing to I_{F3}. Concerning the values, see Table 7.9. At $t=3$ *min 51 sec* the fuses in phase A and C operated and the load breaker opened.

	$I_{F0,peak}$ [A]	$I_{F1,peak}$ [A]	$I_{F1,peak}/I_{F0,peak}$	$I_{F2,peak}$ [A]	$I_{F2,peak}/I_{N,peak}$ [A]	$I_{F3,peak}$ [A]	$I_{F3,peak}/I_{F0,peak}$ [A]
Phase A	11.2	12.6	1.13	145	6.4	5.75	0.51
Phase B	−11.2	−11.2	−1.0	−11.2	−0.5	−11.2	−1.0
Phase C	−11.2	-	-	145	6.4	16	1.43

Table 7.9 Currents in the medium voltage terminals before and after the short circuit was established.

Load currents:

The records of the load currents are shown in Figure 7.15.

Stationary, and before the short circuit was established the load currents are called i_{f0}. In the period $t=2432$ *ms* to $t=3111$ *ms* the load currents are called i_{f2}. After $t=3111$ *ms* the load currents are called i_{f3}. For the values, see Table 7.10.

Pressure in the transformer tank:

Figure 7.16 shows the current I_A and the pressure p for transformer no.5. The pressure starts to increase at $t=2466$ *ms* (34 ms after the fault developed in the coil). The maximum pressure

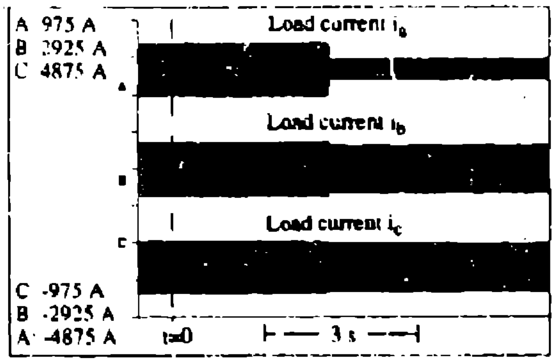


Figure 7.15 The records of the load currents in transformer no.5.

	$i_{f0,peak}$ [A]	$i_{f2,peak}$ [A]	$i_{f2,peak}/i_{f0,peak}$	$i_{f3,peak}$ [A]	$i_{f3,peak}/i_{f0,peak}$
Phase A	514.8	530.4	1.03	198.9	0.39
Phase B	510.9	522.6	1.02	456.3	0.89
Phase C	514.8	507.0	0.98	475.8	0.92

Table 7.10 Load currents in transformer no.5.

$p_{max}=187$ *mbar* is reached at $t=3137$ *ms*. The average pressure rise in this period is $dp/dt=0.28$ *mbar/ms*.

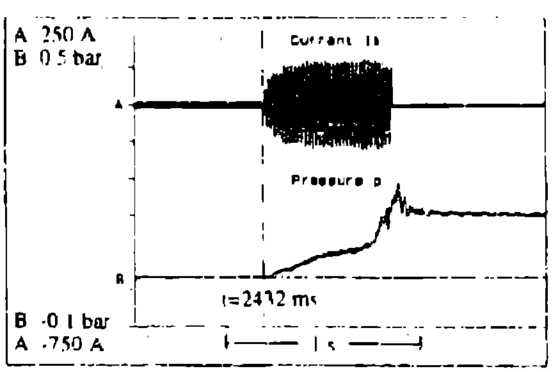


Figure 7.16 The current I_A and the pressure p for transformer no. 5

In the period $t=2466\ ms$ to $t=2994\ ms$ the average pressure rise is $dp/dt=0.13\ mbar/ms$.

In the period $t=2994\ ms$ to $t=3137\ ms$ the average pressure rise is $dp/dt=0.81\ mbar/ms$.

Signal from the gas actuated Buchholz relay:

The alarm signal (GA) was actuated at $t=5170\ ms$, i.e. 2728 ms after the fault developed further inside the coil. Then the pressure was $p_{GA}=125\ mbar$.

Signal from the pressure actuated relay:

The signal from the "Alarm 1-terminals" on the pressure actuated relay (PR) was not actuated during the first 57 sec of the test. This is not surprising since the maximum pressure was less than the pressure that is needed to operate this relay.

Observations from the video recordings:

2.6 sec after the short circuit was established, the gas bubbles were flowing out from coil no.2. About 0.4 sec later the turns in coil no.2 moved upwards, followed by some small bubbles. 4 turns from the upper part of this coil moved downwards outside the coil.

At $t=1\ min\ 2\ sec$ two of the 4 turns mentioned above moved downwards to coil no.3. It is also observed that hot oil was flowing upwards along the coils.

At $t=3\ min\ 47\ sec$ the fault continued. Coil no.2 disintegrated, and turns from this coil moved downwards to coil no.3.

4 sec later a light flash and a crack was observed. Then also coil no.3 is exposed to large mechanical forces. Large quantities of gas was produced. and the transformer oil became black At the time the crack was observed the whole transformer shook.

About 100 ms after the light flash was observed, the transformer tank cracked just below the corrugated plate on the front. Because of the high pressure inside the tank, oil started to flow out with high velocity.

Dissection of the transformer after the test:

The coils in phase B and C were not damaged. The medium voltage coil in phase A was completely damaged. See Figure 7.17. Many turns are melted off, and the mechanical destruction is considerable. In coil no.2 almost all the insulation varnish is carbonized. There has also been an earth fault between the top of coil A and the yoke. (A small part of the yoke has melted).

Also the low voltage coil in phase A was mechanically damaged. The lower part of the coil was deformed. The transformer tank got a crack just below the corrugated plate on the front and oil flowed out.

Figure 7.17 The MV winding on limb C after the test on transformer no.5.

7.5 A BRIEF COMPARISON OF THE RESULTS FROM THE TESTS

In this chapter the following results will be dealt with:

- time Δt from the short circuit between neighbouring turns was established until the fault developed further
- time and pressure when the gas- or pressure actuated relays operated
- amplitudes of the currents and the phase voltages the 6 first periods after the faults developed further
- maximum currents measured (when no earth fault was established)
- a brief discussion of the reaction of different protecting schemes.

7.5.1 Time until the fault developed further

Table 7.11 gives a survey of the time Δt from the short circuit between neighbouring turns was established until the fault developed further in the coil. The average rise in the peak value from the three first electrical periods after the short circuit is established is also calculated.

It is seen that the current rise in phase A varies considerably from one test to another (tests on transformers number 1, 3 and 4 can be compared, since they are YNy0-connected). One reason for this can be that the contact resistance in the contactor varies from one test to another. The conductor resistance is also smaller in transformer 3 compared to transformer 1 and 4.

Transformer number	Δt [ms]	$I_{A1,peak}/I_{A0,peak}$
1	1752	1.37
3	1712	1.20
4	3206	1.22
5	2432	1.13

Table 7.11 Time Δt from the short circuit is established until the fault develops further, and the current rise after the short circuit between neighbouring turns was established.

From the recordings of the currents it is also seen that after the short circuit was established the temperature and the conductor resistance is increasing, and consequently the current is decreasing (see Figure 7.6 (a)).

7.5.2 Time and pressure when the gas- or pressure actuated relays operated

Table 7.12 gives a survey of the time and pressure when the gas- or pressure actuated relays operated. Since there was no gas-production before the short circuit between two neighbouring turns had developed further, all times are measured from the time the faults developed further.

Transf. no.	Δt_{GA} [ms]	p_{GA} [mbar]	Δt_{GR} [ms]	p_{GR} [mbar]	Δt_{PR} [ms]	p_{PR} [mbar]
1	521	79	598	100	-	-
2	>29.000	?	>29.000	?	-	-
3	No oper		No oper.		-	-
4	2236	150	-	-	3607	230
5	2738	125	-	-	>57.000	?

Table 7.12 Times and pressures when the gas- and pressure actuated relays operated.

7.5.3 Current and voltage amplitudes after the fault developed further in the winding on limb A

Current amplitudes the first six electrical periods after the fault developed further:

Figure 7.18 gives a survey of the peak-peak/2 values of the currents in the medium voltage terminals the six first periods after the fault developed further in the transformers. (This value is

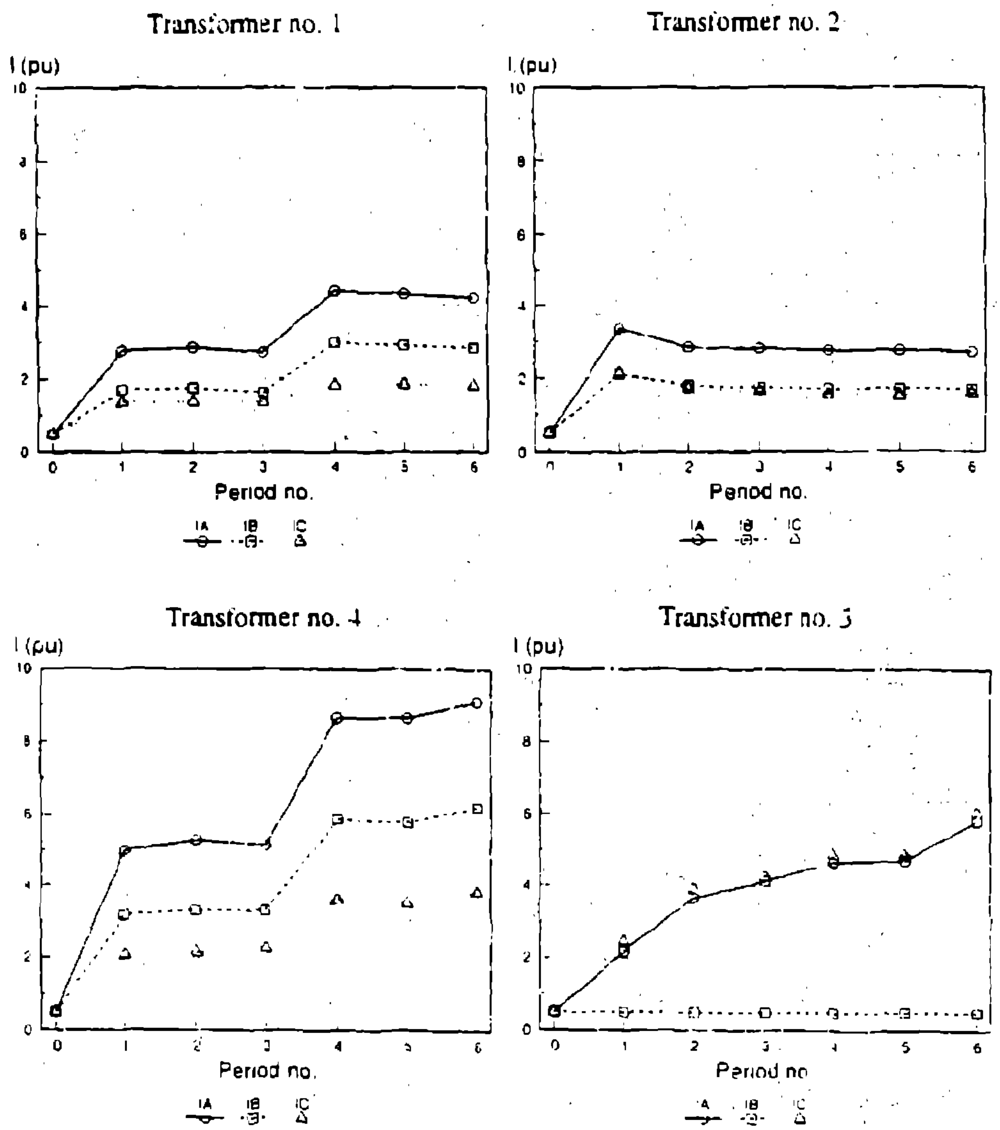


Figure 7.18 The peak-peak/2 values of the currents in the medium voltage terminals for transformer no.1, 2, 4 and 5 the first 6 periods after the fault has developed further in coil A.

almost identical to the peak value). The currents are measured in p.u. values of the nominal peak value of the current. ($1\ pu = \sqrt{2} \times I_N$ where $I_N = 15.9\ A$ for transformer no.1, 4 and 5, and $I_N = 15.15\ A$ for transformer no.2.)

Voltage amplitudes the first six electrical periods after the fault developed further:

Figure 7.19 gives a survey over the peak-peak/2 values of the voltages between phases and the neutral on the medium voltage terminals of the transformers the six first periods after the fault developed further. The voltages are measured in p.u. values of the nominal peak value of the

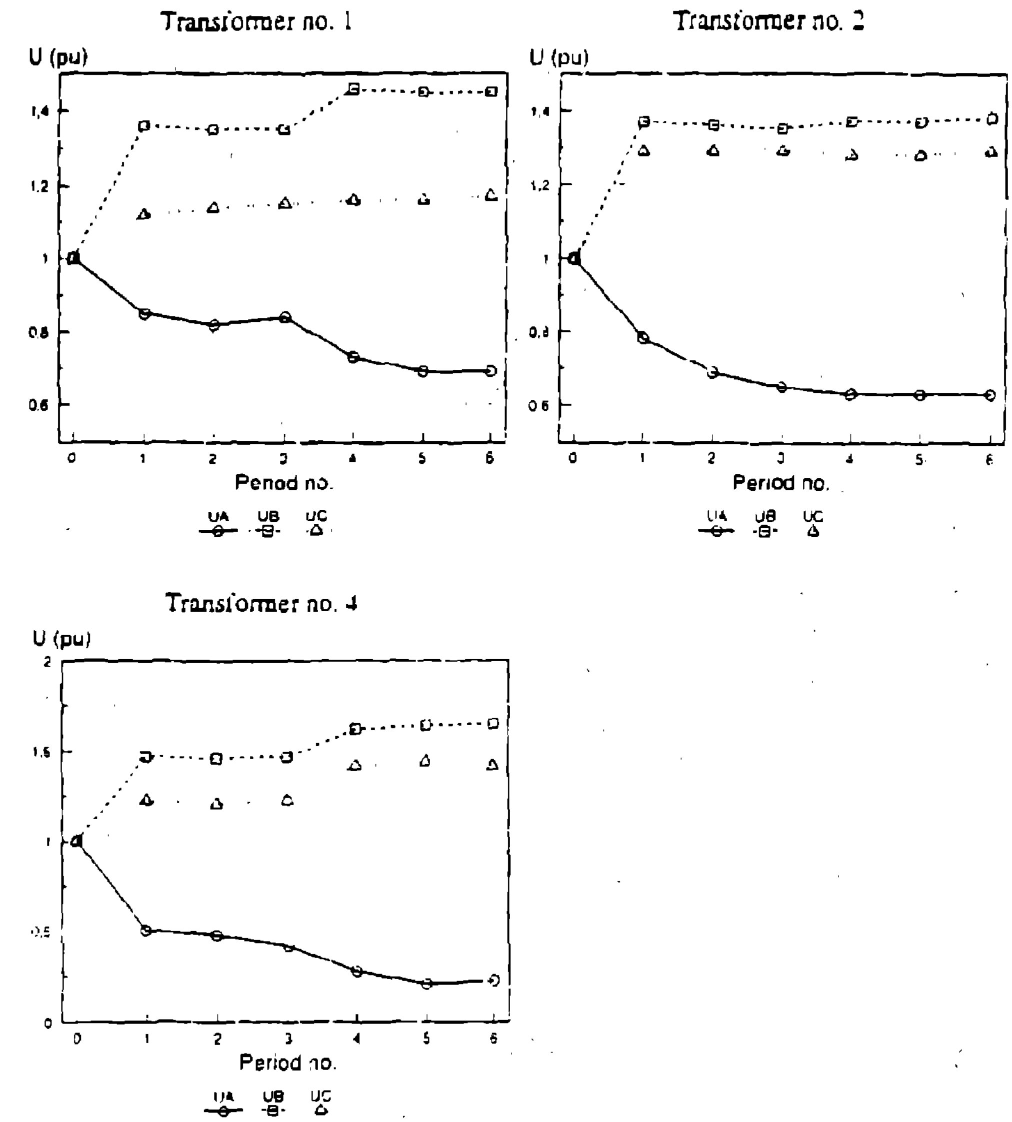


Figure 7.19 The peak-peak/2 values of the phase to neutral voltages on the medium voltage terminals for transformer no 1, 2, and 4 the first 6 electrical periods after the fault has developed further in coil A

phase voltage. ($1\ pu = \sqrt{2} \times \frac{U_N}{\sqrt{3}} = 9.33\ kV$.)

It is seen from Figure 7.19 that the potential of the neutral moves towards the potential of the phase with the short-circuited turns (phase A in these tests).

Current amplitudes in phase A the first second after the fault developed further:

Figure 7.20 gives a survey over the peak-peak/2 values of the currents in the medium voltage terminals the first second after the fault developed further in the transformers.

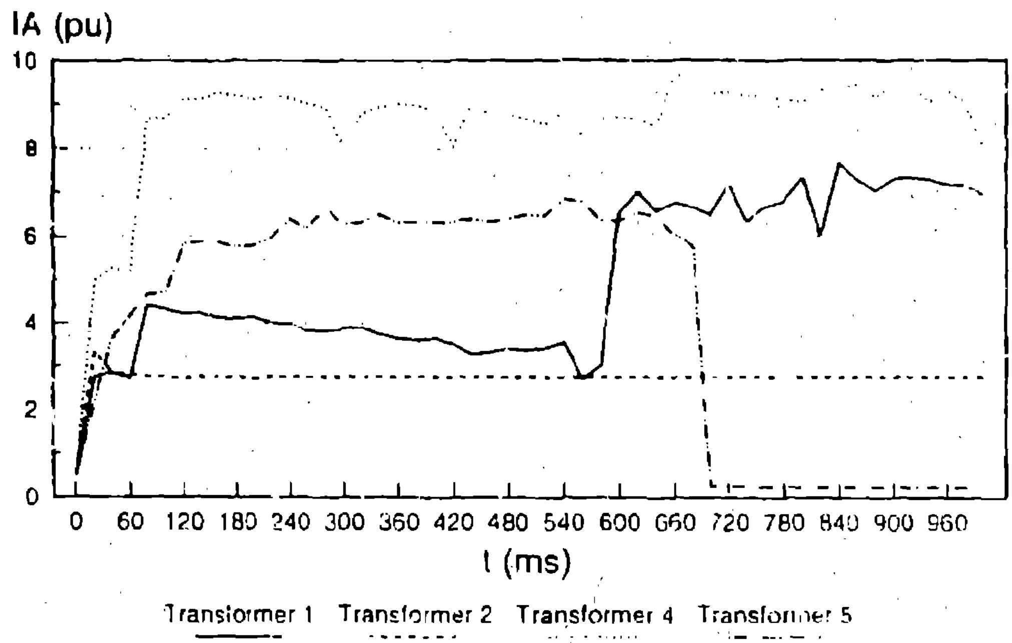


Figure 7.20 The peak-peak/2 values of the currents in phase A for transformer no.1, 2, 4, and 5 the first second after the fault has developed further in coil A

Maximum peak currents in the tests:

When no earth fault was established the maximum peak currents were measured to be as shown in Table 7.13. The currents may have been heavier in the period after the measured interval.

Phase angle between the respective currents and voltages on the medium voltage terminals:

Figure 7.21 shows the records of the current I_A and the voltage U_A for transformer no.1, 2 and 4, and I_A and U_{AC} for transformer no.5. The records show the currents and voltages three electrical periods before, and three electrical periods after the fault has developed further in the coil.

Transformer no.	1	2		4	5
		First test	Second test		
$I_{A,peak\,max}/I_{N,peak}$	7.3	3.4	9.7	11.2	6.9

Table 7.13 Maximum peak currents (I_A) that were measured in the tests when no earth faults were established

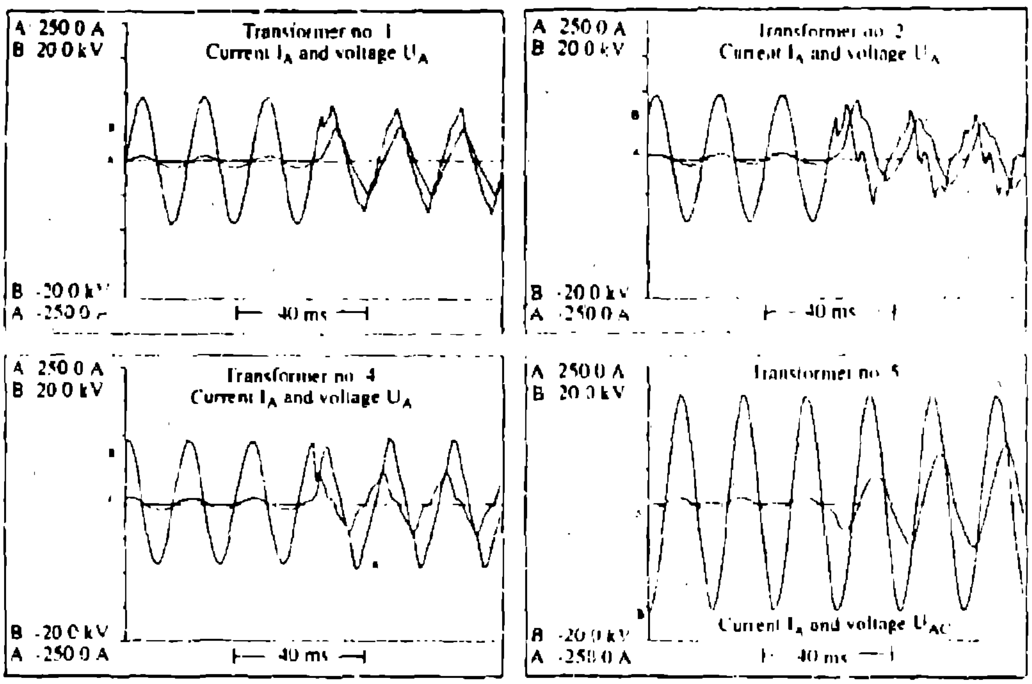


Figure 7.21 Currents and voltages before and after the fault has developed further in the coil

From the tests it is seen that the currents become more and more inductive when the number of short-circuited turns in one phase increases.

7.5.4 Protection against the faults

From Table 7.11 in section 7.5.1 it is seen that it is almost impossible to detect a short circuit between two neighbouring turns with an ordinary short circuit over-current relay, because the increase in the line current is small compared to the load current of the transformer. From Figure 7.18 on page 134 and Figure 7.20 it is seen that when a short circuit between two neighbouring

turns has developed further (transformer no. 1, 4 and 5) so that a larger part of the coil is short-circuited, the currents quickly reach values that could easily be detected with correct dimensioned over-current relays.

A more detailed discussion about different protection schemes for the transformers tested and described in this chapter will be given in section 9.6.1.

7.6 CONCLUSIONS

The following main results and conclusions can be drawn from the tests:

- A short circuit between two neighbouring turns developed in two directions:
  - the short-circuited turn melted off, but contact was probably established between two neighbouring turns, whose insulation varnish was damaged by the high temperature in the short-circuited turn. The transformer appeared to work as normal after this.
  - the fault developed further, and other turns were involved in the short circuit.
- The time from the short circuit was established until the fault developed further was measured to be 1.75-3.2 seconds.
- The primary line currents increased with only 13-17% when only one MV turn was short-circuited[1].
- About 100 ms after the short circuit between neighbouring turns developed further, the line currents had increased to about $4.2 - 8.6 \times I_{N,peak}$ for the transformers.
- The maximum measured peak values of the primary line current in the tests were $6.9 - 11.2 \times I_{N,peak}$
- When two neighbouring layers were short-circuited[2], the time until the fault developed further was more than 29 seconds. (It was probably about 40 s.). In the same test, the MV winding on limb B was also damaged.
- In the tests on the Yyn0 connected transformers, the potential of the neutral on the MV side of the transformers moved towards the potential of the phase with the short-circuited turns. (This is in accordance with section 4.4.1) The voltage between the faulty phase A and the neutral decreased very fast when the number of short-circuited turns involved in the short circuit increased.
- When a large part of the turns was involved in the short circuit, the core saturation increased. This lead to increased leakage flux in the transformer tank, and increased temperature of the transformer tank
- In the test with the Dyn11 connected transformer, the fault seemed to disappear 680 ms after

1 The transformers were secondary loaded with ohmic resistances to about $0.5xS_N$ in the tests.

2. About 14% of the turns on limb A were short-circuited

the fault developed further. 3 min 44 sec later the fault continued again, and 4 sec later a light flash and a crack was observed. The coils on limb A were exposed to large mechanical forces, and the line currents became very high[1]. This test showed that the fault in the coils can be intermittent.

- In all the tests with short circuits between neighbouring turns, where the fault developed further, gas bubbles were observed flowing out from the faulty windings. In some of the tests large amounts of gases were produced.
- The gas actuated Buchholz-relays operated very satisfactorily both for the transformers with conservator, and for the transformers of the hermetically-sealed type.
- By dissection of the transformers it was found that in 4 of the 5 transformers, parts of the MV coils on the faulty limb were completely damaged. Parts of the coils had melted, and "craters" were often observed in the coils. It is clear that the destructions were close to what have been observed on faulty transformers removed from service. It can be concluded that the tests with short circuits between turns described in this chapter are very realistic with regard to the great majority of internal failures in distribution transformers.

1. The currents were not measured, but current limiting fuses of the type CEF-160A from ABB operated

8 FULL SCALE TESTS WITH INTERNAL POWER ARCS IN DISTRIBUTION TRANSFORMERS

8.1 SUMMARY

This chapter deals with internal power arcs in mineral-oil-filled distribution transformers. Eight tests have been carried out with internal arcs between two neighbouring phases on the medium voltage side of distribution transformers with rated power from 50 to 500 kVA. The tests were carried out at the short circuit laboratory NEFI outside Skien in December 1990[1]. The prospective short circuit current was $I_{sc,pros} = 5.17\ kA_{rms}$. The arcs were established with ignition wires connected close to the line end of the transformer windings.

The arcing time in the tests without current limiting fuses in series with the transformers varied from 7 to 150 ms. In two of these tests, the arcs extinguished by itself. In the two tests with current limiting fuses in series with the transformers, the arcs exinguished after 2.2 and 3.1 ms respectively. In these two tests no external damage of the transformer tanks was observed.

The time from the arcs were established until the first peak value of the pressure in the upper part of the transformer varied from 7.1 to 11.6 ms.

In three of the tests the transformer tank cracked. In one of these tests oil was ignited, and an explosive fire caught immediately. In another test, two of the medium voltage bushings exploded, and flames were observed to reach about 4-5 meters above the transformer.

The tests showed that with momentary development of internal power arcs between phases on the MV side of distribution transformers, it is very important to reduce the arcing time and the arcing energy to a minimum to avoid cracking or explosion of the transformer tank. Current limiting MV fuses are very effective as protection against this seldom or almost never occurring faults.

8.2 EXPERIMENTAL ARRANGEMENTS FOR THE MEASUREMENTS

In this section the arrangements for the power supply, the measuring units and the short circuit arrangement will be described

8.2.1 Schematic description of the test arrangement

Figure 8.1 shows the test arrangement for the short circuit tests at NEFI. The transformers were supplied single phase. The prospective line voltage was 21.9 kV_{rms}, and the prospective short circuit current was measured to be 5.17 kA_{rms}.

1. The tests are previously described in [33] and [53]

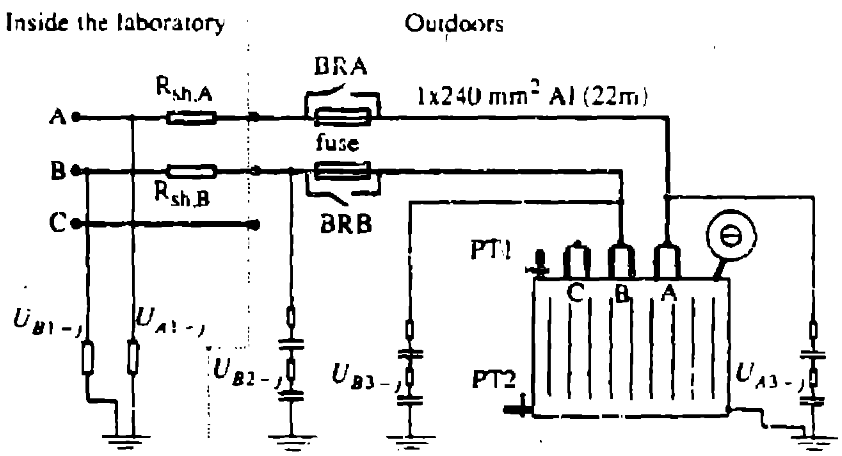


Figure 8.1 Schematic description of the test arrangement for short circuit tests at NEFI.

In Figure 8.1 it is necessary to give following list of abbreviations:

PT1	: Pressure transmitter situated at the cover of the transformer.
PT2	: Pressure transmitter situated on the drain cock in the lower part of the transformer tank.
BRA and BRB	: The breakers are closed in the tests with no fuses in series with the transformers.
$R_{sh,A}$ and $R_{sh,B}$	: Non-inductive ohmic shunts for the current measurements.

Phase C on the MV side and the low voltage terminals were open in all the tests.

To catch the oil which could leak from the transformers, the transformers were located in an open container during the tests.

Current measurements:

The currents were measured with non-inductive ohmic shunts with values 0.01 mΩ. They were located inside the laboratory.

Voltage measurements:

The voltages U_{B2-j}, U_{B3-j} and U_{A3-j} were measured with damped capacitor dividers. U_{B1-j} and U_{A1-j} were measured with parallel resistor-capacitor dividers. The voltage across the arc is measured as $U_{arc,3} = U_{B3-j} - U_{A3-j}$. Afterwards it was observed that during the measurements of the voltage $U_{arc,3}$, the zero line had an offset error of about 600 V. Because of this the results from the power calculations are somewhat misleading (the power in the positive and negative period differs to much).

In some of the records the voltage $U_{arc,1} = U_{B1-j} - U_{A1-j}$ is calculated. This voltage also includes the voltage drop across the cables and the fuses. In the tests with fuses in series with the

transformer the voltage across one of the fuses is calculated as $U_{fuse} = U_{B2-j} - U_{B3-j}$.

Pressure transmitters:

All the pressure transmitters used in the tests were of the piezoresistive type. In some of the tests two pressure transmitters were installed at the cover or on the drain cock in the lower part of the transformer tank.

8.2.2 Signal transmission, data sampling and data storage

Figure 8.2 gives a schematic description of the signal transmission system. The measuring instruments (voltage dividers, non-inductive shunts etc.) and the electrical to optical transmitters were situated either inside the laboratory or outdoors. The optical to electrical receivers, the transient recorders and the PC were placed in the control room. All signals were transmitted to the control room by optical fibers.

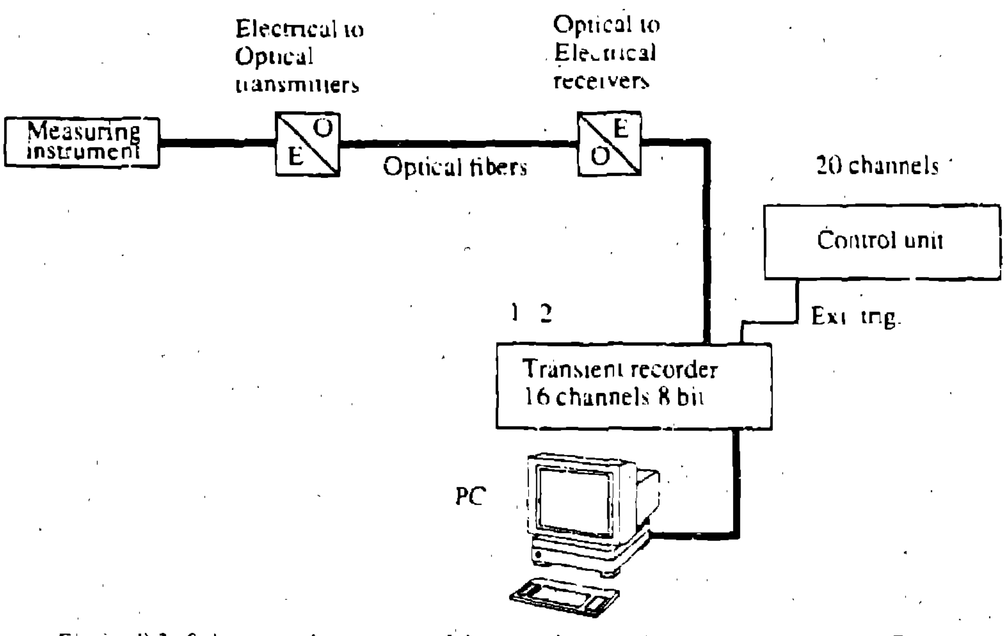


Figure 8.2 Schematic description of the signal transmission system used at NEFI.

8.2.3 Short circuit arrangement in the transformers

The arcs inside the transformers were established with arc ignition wires, which were either Ø=0.5 mm Cu-conductors or Ø=0.08 mm resistance wires with R=20… m. In the tests the arcs were established in three different ways, see Figure 8.3. In case (a) the … ion wire was situated around the phase dividing insulation, and in case (b) it was situated b… en the phase dividing

insulation and the yoke insulation. In case (c) the ignition wire was situated between the leads from the coils to the HV bushings on the clamping section to the yoke.

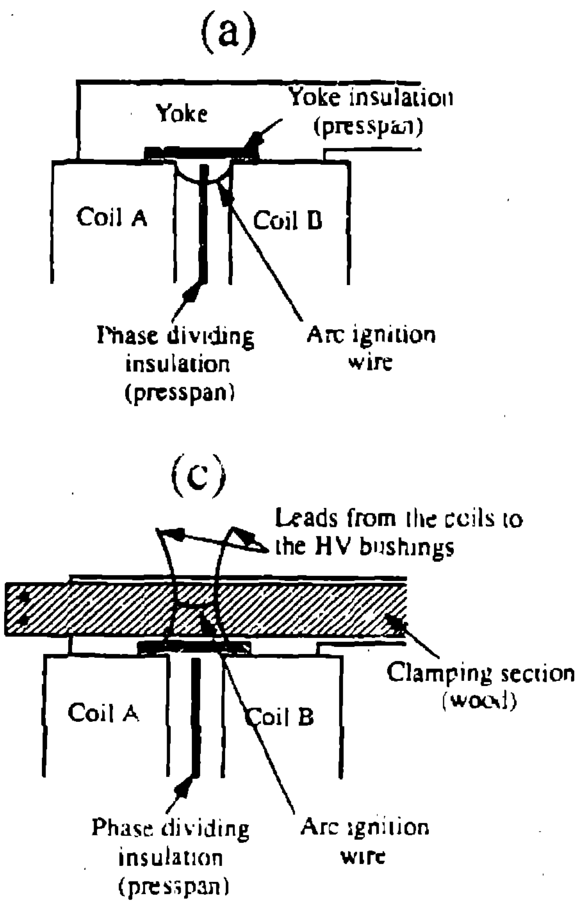


Figure 8.3 Location of the arc ignition wire.

8.3 A SURVEY OF TYPES OF TRANSFORMERS AND TYPES OF FAULTS THAT WERE TESTED

As mentioned earlier, eight tests were done with internal arcs between two neighbouring phases. Table 8.1 gives a survey of the test conditions for the eight tests. In all the tests the arc ignition wire was connected close to the line end of the transformer windings.

Test no.	Transformer rating [kVA]	Placing of the arc ignition wire (See Figure 8.3)	Type and length of arc ignition wire [mm]	Adjusted clearing time for circuit breaker [ms]	Fuses in series
1	75	(a)	A [1] 35	46	-
2	75	(b)	A 95	46	-
3	500	(b)	A 100	46	-
4	500	(b)	B [2] 100	200	CEF-40A[3]
5	50	(b)	B 80	200	CEF-25A[3]
6	50	(b)	B 80	150	-
7	100	(c)	B 60	150	-
8	500	(b)	A 80	150	-

[1] A : Ø=0.5 mm Cu-conductor
[2] B : Ø=0.08 mm resistance wire with R=200 Ω/m
[3] Current limiting MV fuses manufactured by ABB.

Table 8.1 Test conditions for the short circuit tests

8.4 A DESCRIPTION OF THE COURSE OF EVENTS IN EACH TEST

In the following a description of the course of events for each test will be given. Only a small selection of records from the measurements is presented in the text.

The presentation will include studies of the following parameters:

- current (I) in the medium voltage terminals (phase A and B)
- voltage (U_{arc}) between the terminals A and B
- pressure in the transformer tank
- observations from the video recordings

8.4.1 Test no.1. (75 kVA, arrangement (a))

The ignition wire was situated around the phase dividing insulation as shown in Figure 8.3(a). The records from the current, the arc voltage and the calculated power input are shown in Figure 8.4

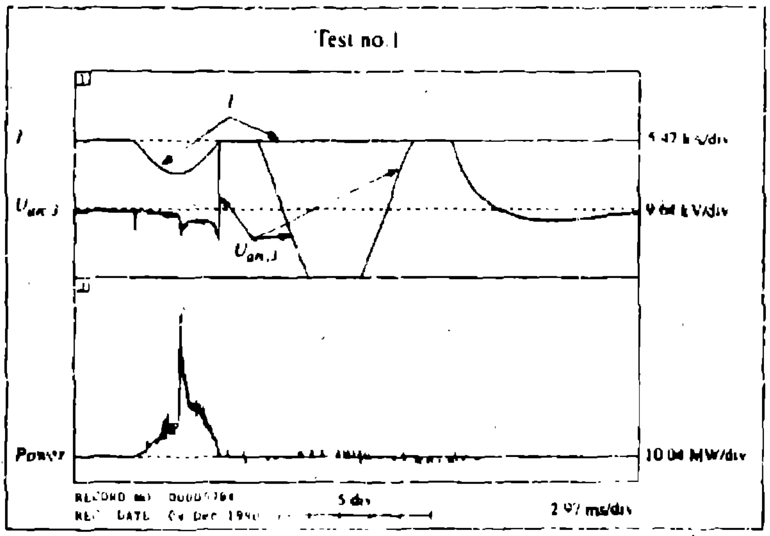


Figure 8.4 Current (I), arc voltage ($U_{arc,3}$), and calculated power in test no. I.

The arc lasted for t_{arc} = 8 ms, and the peak value of the current was measured to be I_{peak} = 5.9 kA. The arc voltage ($U_{arc,3}$) increased considerably after t = 4.5 ms. The reason for the increase in the arc voltage is unknown, since the transformer was not opened after the test. But it is possible that an arc ignited towards the transformer tank.

The pressure started to rise at $t \approx 5$ ms, and the maximum pressure p_{max} = 0.7 bar was reached at $t \approx 9$ ms. (The signals from the pressure transmitters included much noise, and it is impossible to make an accurate reading from the pressure recordings).

The transformer cover was bent, but no oil leakage was observed after the test.

8.4.2 Test no.2. (75 kVA, arrangement (b))

The ignition wire was situated between the phase dividing insulation and the yoke insulation as shown in Figure 8.3(b). The records from the pressure, current and arc voltage are shown in Figure 8.5.

The arc was established 1.26 ms after the voltage was turned on. After this the arc lasted until the circuit breaker opened 44.7 ms later. The peak value of the current was measured to be I_{peak} = 8.6 kA. The pressure started to rise about 3.7 ms after the arc was established. The first peak value was reached 11.6 ms after the arc was established, and was measured to be $p_{T1,peak}$ = 4.3 bar.

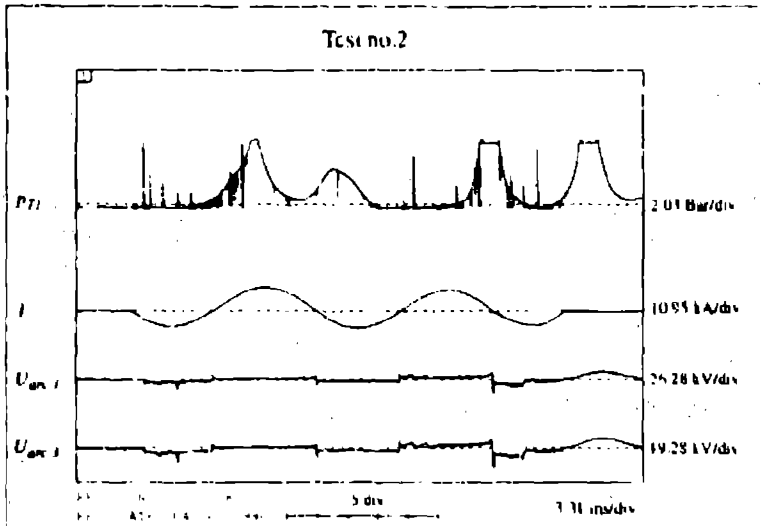


Figure 8.5 Pressure (p_{T1}), current (I) and arc voltage ($U_{arc,1}$ and $U_{arc,3}$) in test no 2

The transformer tank cracked just below the corrugated plate in the lower part of the tank, and oil flowed out. Also in this test the transformer cover was bent, and from the video recordings it can be observed that some oil spouted out just under the transformer cover during the test.

8.4.3 Test no.3. (500 kVA, arrangement (b))

The ignition wire was situated between the phase dividing insulation and the yoke as shown in Figure 8.3(b), apart from the fact that this transformer had no yoke insulation. The records from the pressure, current and arc voltage are shown in Figure 8.6.

The arc was established 1.23 ms after the voltage was turned on. After this the arc lasted until the circuit breaker opened 44.8 ms later. The peak value of the current was measured to be $I_{peak} = 8.4\ kA$. The pressure started to rise about 7 ms after the arc was established. The first peak value of the pressure in the upper part of the tank was reached about 11 ms after the arc was established, and was measured to be $p_{T1,peak} = 2.8\ bar$. The first peak value of the pressure in the lower part of the tank was reached 16 ms after the arc was measured and was measured to be $p_{T2,peak} = 2.2\ bar$.

No external damage of the transformer tank was observed in this test.

8.4.4 Test no.4. (500 kVA, arrangement (b), MV fuses in series)

The transformer was of the same type as in test no.3, and the ignition wire was located between

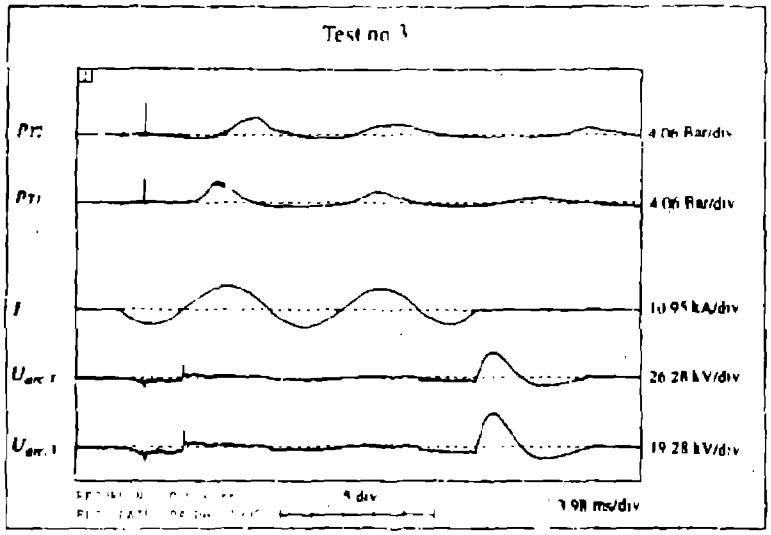


Figure 8.6 Pressure (p_{T1} and p_{T2}), current (I) and arc voltage ($U_{arc,1}$ and $U_{arc,3}$) in test no 3.

the phase dividing insulation and the yoke as shown in Figure 8.3(b). Current limiting fuses of the type CEF-40A from ABB were placed in series with the transformer. The records from the pressure, current, arc voltage and voltage across the fuse in phase B are shown in Figure 8.7.

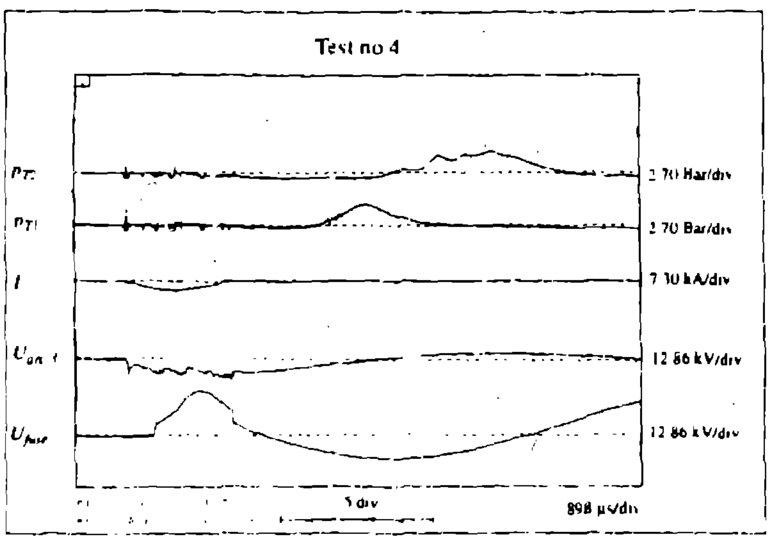


Figure 8.7 Pressure (p_{T1} and p_{T2}), current (I), arc voltage ($U_{arc,3}$) and fuse voltage (U_{fuse}) in test no 4.

The arc was established very short time after the voltage was turned on. The voltage across the fuse in phase B started to build up at $t=0.9\ ms$. One of the fuses broke the current at $t = 3.1\ ms$. The current was limited to $I_{peak} = 2.1\ kA$.

The pressure started to rise at $t = 5.5\ ms$, and the first peak value was reached at $t = 7.1\ ms$, and was measured to be $p_{T1,peak} = 2.1\ bar$.

No damage of the transformer was observed in this test (neither in the windings nor on the transformer tank)

8.4.5 Test no.5. (50 kVA, arrangement (b), MV fuses in series)

The ignition wire was situated between the phase dividing insulation and the yoke insulation as shown in Figure 8.3(b). Current limiting fuses of the type CEF-25A from ABB were placed in series with the transformer. The records from the pressure, current, arc voltage and voltage across the fuse in phase B are shown in Figure 8.8.

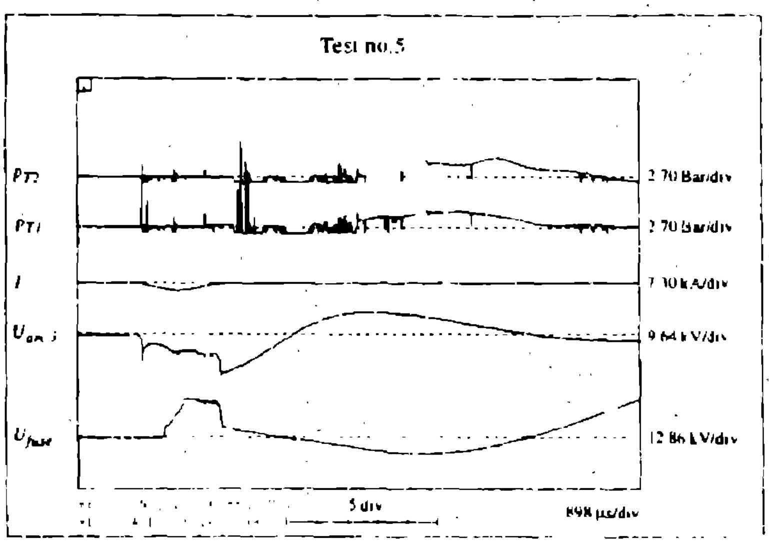


Figure 8.8 Pressure (p_{T1} and p_{T2}), current (I), arc voltage ($U_{arc,3}$) and fuse voltage (U_{fuse}) in test no.5.

The arc was established very short time after the voltage was turned on. The voltage across the fuse in phase B started to build up at t=0.6 ms. One of the fuses broke the current at $t = 2.2\ ms$. The current was limited to $I_{peak} = 1.6\ kA$.

The pressure started to rise at $t = 6\ ms$, and the first peak value was reached at $t = 9\ ms$ in the

upper part of the tank and was measured to be $p_{T1,peak} = 1.5\ bar$. The first peak value of the pressure in the lower part of the transformer was reached at $t = 11.5\ ms$, and was measured to be $p_{T2,peak} = 1.7\ bar$.

There was not observed any visible external damage of the transformer tank in this test. But on the video recordings it was observed a flashover on the HV bushing in phase C (not connected).

8.4.6 Test no.6. (50 kVA, arrangement (b))

The transformer was of the same type as in test no.5, and the ignition wire was also in this test situated between the phase dividing insulation and the yoke as shown in Figure 8.3(b). The records from the pressure, current and arc voltage are shown in Figure 8.9.

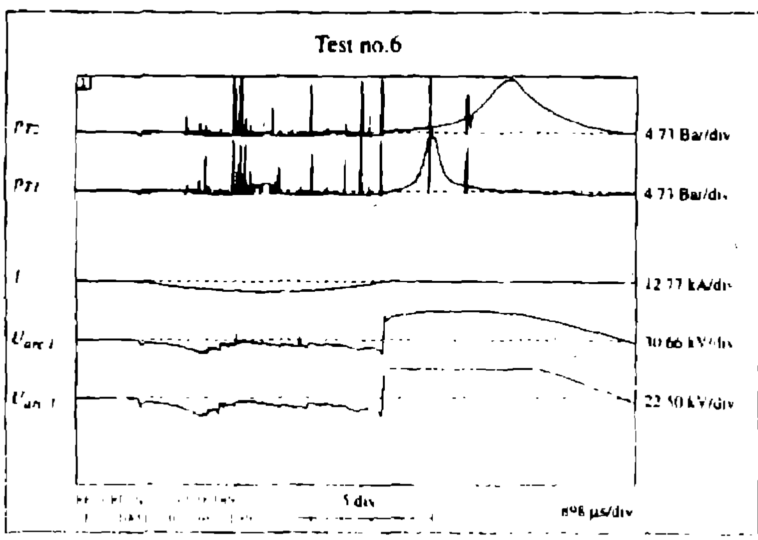


Figure 8.9 Pressure (p_{T1} and p_{T2}), current and arc voltage ($U_{arc,1}$ and $U_{arc,3}$) in test no.6.

The arc was also in this test established a very short time after the voltage was turned on. The arc extinguished after $t = 7\ ms$. In this test the arc voltage was large (5.5-6 kV), and the peak value of the current was measured to be $I_{peak} = 4.3\ kA$. From this it is seen that the arc voltage limited the short circuit current.

The pressure started to rise about 7 ms after the arc was established. The first peak value of the pressure in the upper part of the transformer was reached at $t = 8.3\ ms$ and was measured to be $p_{T1,peak} = 8.7\ bar$. The first peak value of the pressure in the lower part of the tank was reached at $t = 11\ ms$ and was measured to be $p_{T2,peak} = 8.5\ bar$.

The transformer tank cracked in the upper part of the tank (just above the corrugated plate). From the video recordings it can be observed oil-mist and liquid transformer oil blowing out from the cracked tank. Also in this test it was observed a flashover on the HV bushing in phase C. but it did not cause any ignition.

8.4.7 Test no.7. (100 kVA, arrangement (c))

The ignition wire was situated between the leads from the coils to the HV bushings on the clamping section to the yoke as shown in Figure 8.3(c). The conductors in the HV coils were made of aluminium. The records from the pressure, current and arc voltage are shown in Figure 8.10.

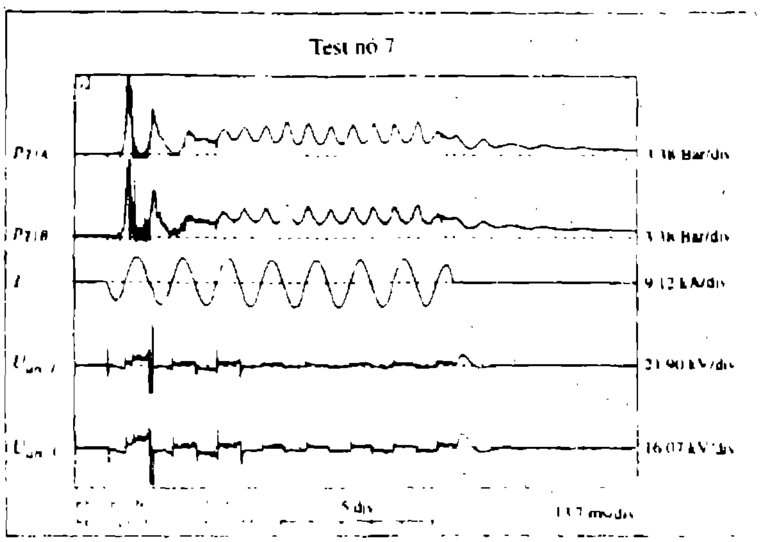


Figure 8.10 Pressure (p_{T1A} and p_{T1B}), current and arc voltage (U_{arc1} and U_{arc3}) in test no.7

The arc was established very short time after the voltage was turned on. After this the arc lasted until the circuit breaker opened 150 ms later, and the peak value of the current was measured to be $I_{peak} = 5.7\ kA$. The pressure was measured with two pressure transducers situated at the cover of the transformer tank. The pressure started to rise at $t = 5\ ms$. The peak value of the pressure was reached about at $t = 10\ ms$ and was measured to be more than 8.5 bar. (The pressure became larger than the adjusted span.)

Just when the current passed zero for the second time, the arc tried to extinguish. This is seen from the recordings of the arc voltage and the current.

From the video recordings it was observed that at first transformer oil sprouted out near one of the HV bushings (one of the attaching bolts for the bushing was destroyed before the test). Oil mist escaped out just under the transformer cover. About 280 ms after the oil sprouted out near the HV bushing and was ignited. It seems as if the oil was ignited by flames coming out just under the cover. After the ignition an explosive fire caught immediately, and the flames were observed to reach about 4 meters above the transformer. From this observations it is obvious that the oil mist and gases outside the transformer tank was ignited after the circuit breaker opened. Then it is obvious that flames, sparks or glowing objects were present in the transformer also some time after the circuit breaker opened. About 1.6 seconds after the fire was ignited it extinguished.

After the test it was observed two carbonized tracks on the transformer tank just opposite the place where the ignition wire was situated. From this observation it is likely that the arc developed into two arcs between the conductors and the transformer tank. In other words, the arc between two phases developed to be an earth fault. It is likely that this happened when the arc tried to extinguish as mentioned above. The transformer tank cracked just below the corrugated plate in the lower corners of the tank, and oil flowed out.

8.4.8 Test no.8. (500 kVA, arrangement (b))

The transformer was the same as used in test no.4 The ignition wire was also in this test situated between the phase dividing insulation and the yoke as shown in Figure 8.3(b). The records from the pressure, current and arc voltage are shown in Figure 8.11.

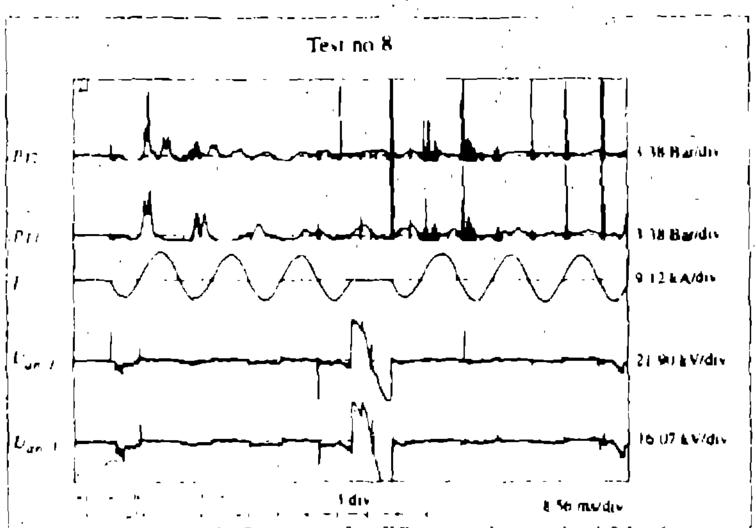


Figure 8.11 Pressure (p_{T1} and p_{T2}), current and arc voltage ($U_{arc\,1}$ and $U_{arc\,3}$) in test no.8.

The arc was established 1.33 ms after the voltage was turned on. After this the arc lasted until

$t = 69\ ms$, and then the arc extinguished. 11.5 ms later the arc was established again, and now it lasted until the circuit breaker opened at $t = 150\ ms$. The peak value of the current was measured to be $I_{peak} = 8.5\ kA$.

The pressure started to rise at $t = 9\ ms$. The peak value of the pressure in the upper part of the tank was reached about at $t = 10.5\ ms$ and was measured to be $p_{T1,peak} = 5.4\ bar$. The peak value of the pressure in the lower part of the tank was reached at $t = 11\ ms$ and was measured to be $p_{T2,peak} = 7.3\ bar$

After the voltage was turned on, a flash of light was observed by the HV bushings and the cover. Immediately afterwards the HV bushings in phase A and B exploded, and filaments were scattered over a big area around the transformer. The flames were observed to reach about 4-5 meters above the transformer. Figure 8.12 shows the situation just after the explosion.

Figure 8.12 The situation just after the bushings exploded in test no.8

About 3.8 seconds after the bushings exploded, the violent fire ceased. But flames were still coming out from the holes after the bushings in the cover for about 40 seconds before the fire was extinguished with a fire extinguisher.

After the test the transformer was opened, and it was observed that arcs to ground had developed. The coils in phase A and B were damaged, but not as serious as expected. Apart from the HV bushings, the transformer tank was undamaged.

8.5 A BRIEF COMPARISON OF THE RESULTS FROM THE TESTS

Table 8.2 gives a survey of the results from the tests. The times t_{pT1} and t_{pT2} are the periods from

Test no.	Fuses	Arcing time [ms]	I_{peak} [kA]	p_{T1} [bar]	t_{pT1} [ms]	p_{T2} [bar]	t_{pT2} [ms]
1	-	8	5.9	~ 0.7	~ 9		
2	-	45	8.6	4.3	11.6		
3	-	45	8.4	2.8	11	2.2	16
4	CEF-40	3.1	2.1	2.1	7.1	2.0	11
5	CEF-25	2.2	1.6	1.5	9	1.7	11.5
6	-	?	4.3	8.7	8.3	8.5	11
7	-	150	5.7	>8.5	10		
8	-	67.7+69.5	8.5	5.4	9.2	7.3	9.7

Table 8.2 A survey of some results from the full scale tests at NEFI.

the arc was established until the first peak values of the pressures were reached.

Table 8.3 gives a survey of the observations during and after the tests.

8.5.1 50 kVA transformers with and without fuses in series (test no.5 and 6)

Test no.5 and 6 can be compared, since the transformers are of the same type, and the arc ignition wires were similarly located in the two tests.

It is seen that the fuses in series with the transformer in test no.5 reduced the peak value of the current to about 37% of the value in test no.6. The time before the arc extinguished ("arcing time" in Table 8.2) was reduced to only 2.2 ms in test no.5 with fuses in series with the transformer. The average arc power was about 5 MW in test no.5, and about 17 MW in test no.6.

The first peak values of the pressures inside the transformer tanks were reached about at the same time after the arcs were established in the two tests. But the pressure in the transformer protected by fuses was only about 20% of the pressure in transformer no 6.

There was not observed any visible external damage of the transformer in test no.5 with fuses in series. In test no 6 the transformer tank cracked in the upper part of the tank, and both oil-mist and oil escaped.

Test no.	Comments
1	The transformer cover was bend, but no oil leakage was observed.
2	The transformer tank cracked just below the corrugated plate in the lower part of the transformer, and oil streamed out. Some oil also spouted out below the transformer cover during the test.
3	No external damage of the transformer tank.
4	No damage of the transformer at all.
5	No external damage of the transformer tank. A flashover on the HV bushing in phase C was observed.
6	The transformer tank cracked just above the corrugated plate at the upper part of the transformer, and both oil-mist and oil spouted out. A flashover on the HV bushing in phase C was observed.
7	Oil-mist spouted out just below the transformer cover. Oil was ignited by flames coming out just below the cover. After the ignition an explosive fire caught immediately. Two carbonized tracks were observed opposite the place where the ignition wire was situated. The tank cracked just below the corrugated plate in the lower corners of the tank.
8	The HV bushings in phase A and B exploded, and flames were observed to reach about 4-5 meters above the transformer.

Table 8.3 Observations made during and after the tests.

8.5.2 500 kVA transformers with and without fuses in series (test no.3, 4 and 8)

Test no.3, 4 and 8 can be compared, since the transformers are of the same type, and the arc ignition wires were similarly located in the three tests.

It is seen that the fuses in series with the transformer in test no.4 reduced the peak value of the current to about 25% of the values in test no.3 and 8. The time before the arc extinguished ("arcing time" in Table 8.2) was reduced to only 3.1 ms in test no.4 with fuses in series with the transformer.

The first peak values of the pressures inside the transformer tanks were reached 7.1-11 ms after the arcs were established in the three tests. It was expected that the first peak values of the pressures in test no.3 and 8 should have been about the same. But the pressure in test no.8 was considerably higher than in test no.3. This indicates that the reproducibility concerning the course of events for this kind of fault is bad.

8.5.3 75 kVA transformers, different location of the arc ignition wires

Test no.1 and 2 can be compared, since the transformers are of the same type. In test no.1 the arc ignition wire was situated around the phase dividing insulation, and in test no.2 it was situated between the phase dividing insulation and the yoke insulation. The course of events for these tests were different. The pressure inside the transformer in test no.2 was considerably higher than in test no.1. This led to more serious damage of the transformer tank.

8.5.4 The time from the arc was established until the first peak of the pressure was reached

From Table 8.2 it is seen that the period from the arc was established until the first peak value of the pressure in the upper part of the transformer was reached varies from 7.1 to 11.6 ms in these tests. Then it seems as if the time from the arc is established until the peak value of the pressure is reached is independent of the arcing time for these transformers. (The transformers used in the tests were all of the conservator type.)

8.6 CONCLUSIONS

The main results and conclusions from the tests are as follows:

- An internal power arc in a distribution transformer may lead to violent rupture of the transformer tank. This may cause ignition and explosion.
- The time from the arcs were established until the first peak value of the pressure was reached was 7.1-11.6 ms.
- In two of the eight tests the arcs extinguished. Even if the arcing time in these tests was only 7 and 8 ms respectively, the pressure inside the transformer tank reached a value that led to crack of the transformer tank in one test, in which both oil mist and oil escaped.
- It seems that larger transformers is more resistant to tank rupture than smaller transformers.
- The tests indicates that the reproducibility for the course of events with this kind of fault is bad.
- With a momentarily development of internal power arcs in oil-filled distribution transformers it is very important to reduce the arcing time and the arcing energy to a minimum to avoid cracking or explosion of the transformer tank.
- Current limiting MV fuses are very effective as protection against this seldom or almost never occurring momentarily developing internal power arcs. This is due to the current limiting capability of the fuses, and the fact that the fuses will discontinue the high prospective currents in a few ms.

9 PROTECTION OF DISTRIBUTION TRANSFORMERS AGAINST INTERNAL FAULTS

9.1 SUMMARY

Ground mounted MV/LV distribution transformers have a high level of reliability. It must therefore be questioned if the decisions made about 50 years ago to provide fuse switches to protect, switch and isolate distribution transformers is still valid today with a very good service experience with this type of transformers. It is conceivable that the transformer could be connected solidly to the system and be provided only with a means of isolation for the use in the unlikely event of a transformer failure. This is not acceptable in most schools of thought because a faulty transformer, however unlikely, which is not rapidly disconnected from the system is a potential fire or explosion risk. In addition, the transformer protection covers not only the transformer but the MV and LV cables connected to the transformer and the busbar of the LV fuse gear. These risks left unprotected are generally regarded as unacceptable.

The first part of this chapter gives a brief description of distribution substations and switchgear. A description of different protection arrangements for the distribution transformers is given.

A discussion of the effectiveness of different protection methods for the experiments with internal short circuits between turns in the MV windings described in chapter 7, the experiments with internal power arcs described in chapter 8 and experiments described in chapter 3 with internal faults in transformers described in the literature will also be given in this chapter.

The most commonly used cable network system in Norway is the mesh networks, and they are usually operated as radial networks. Earlier the MV switchgear in the MV/LV substations were air-insulated. During the last 5-8 years, a new generation of environmental proof units applying SF_6 as an insulating medium have increased their share of the market in Norway. The most used switchgear system in the cable network is the so called ring main unit (RMU) with two or more breakers for MV feeders, and one breaker for the transformer. It is expected that the solution with satellite substations will be more popular in the future.

The main purpose of the distribution transformer overcurrent protection scheme is as follows,

- protect the distribution system from line lockout in the event of a transformer failure
- protect the transformers against severe overloads or secondary faults
- insure the safety of the general public and operating personnel by protecting against disruptive transformer tank rupture

Fuses as transformer protection have one significant advantage because they are current limiting when interrupting full rating fault currents. Some disadvantages for the fuses can be listed as follows;

- the fuses generate considerable heat

- mounting difficulties of the fuses together with SF_6 switchgear
- the fuses have distinct shortcomings in the overload range

Some general advantages of the circuit breaker as a transformer overcurrent protection are as follows;

- full integration of the SF_6-insulated switchgear
- low heat generation
- unlimited current rating for the protection of distribution transformers

The main disadvantage for the circuit breaker is the lack of fault limiting capability.

Tests[1] with internal short circuits between neighbouring turns in the MV windings of distribution transformers have shown that the line currents quite fast reach values that could easily be detected by specially designed microprocessor overcurrent relays. Depending on the time-current characteristic of MV current limiting fuses, the fault currents may also be cleared by such fuses. Tests with internal short circuits between turns also showed that gas actuated relays (Buchholz-type) operated very satisfactorily and fast, both for transformers with conservator and for transformers of the hermetically-sealed type.

Tests with momentarily development of internal power arcs between phases on the MV side of distribution transformers have shown that with this type of fault it is very important to reduce the arcing time and the arcing energy to a minimum to avoid cracking or explosion of the transformer tank[2]. Current limiting MV fuses are very effective as protection against this kind of fault. It must be noticed that a fault with a momentarily development of an internal power arc is extremely rare.

To get a good protection against overload currents, one of the following protective measure can be done;

- install LV main fuses between the transformer and the LV busbars
- install a LV circuit breaker between the transformer and the LV busbars
- use a thermal relay situated between the distribution transformer and the LV busbars to trip the MV fuse-loadbreaker when the transformer is loaded above the trip value[3].

1. The tests on "Munkvoll" described in chapter 7. These tests represent the great majority of internal failures in distribution transformers.
2. The tests on "NEFI" described in chapter 8. The results is also confirmed in the literature [38], [39].
3. The thermal relay can be combined with the measuring transformers usually situated between the distribution transformer and the LV busbars.

9.2 DISTRIBUTION SUBSTATIONS AND SWITCHGEAR

The MV switchgear of a substation has the following functions:

- to provide section points for the system which can be closed or opened with the system alive.
- to isolate faulty cables or lines
- to protect and isolate the MV/LV distribution transformer when required.

This section gives a brief survey of some MV/LV substation arrangements.

9.2.1 Distribution substations situated in the cable network

The MV/LV substations (buildings) situated in the MV cable network exists in many different designs. Earlier the substations were usually built on site, but today they are usually prefabricated. The switchgears are often situated in separate rooms inside industrial buildings or other large buildings.

Earlier the switchgears were normally air-insulated. During the last 5-8 years a new generation of environmental proof units applying SF_6 as an insulating medium have occupied much of the market in Norway.

Various switching and isolating arrangements are in operation. The most used system in the cable network is the so called ring main unit (RMU). The RMU's do usually have two breakers for MV feeders and one breaker for the transformer. See Figure 9.1(a) and (b). The system is often called 2C+T RMU. Sometimes the switchgears have 3 or more breakers for MV feeders. Traditionally load breakers have been used for the MV feeders, and load breakers in combination with so called expulsion fuses or current-limiting fuses have been used as transformer overcurrent protection. Figure 9.1 shows some different arrangements used in MV/LV substations in the cable network.

Figure 9.1(c) shows the so called ring disconnect unit (RDU). Because of the plug connections, these can only be operated when the substation is without voltage. The RDU incorporates a busbar and a contact assembly moulded into a polymeric housing, with connections between the tee and the incoming circuits made by means of cast resin plugs incorporating an appropriate metal link. Alternative plugs are available to provide circuit isolation, earthing and testing features. A number of plug-type devices have been tried by Eastern Electricity in the U.K., and it is said that their use does imply limitations both for the operation engineer and the customer [54]. The time required to operate equipment which does not include integrated switching and earthing facilities is much greater than for conventional switches. In [54] it is said that it is sufficient to require a large cost saving before plug or bolted disconnectors are likely to receive general acceptance as replacements for the RMU.

It seems as if the solution with satellite substations (see Figure A.6 on page 182) will be more and more popular. Some different solutions for satellite substations are shown in Figure 9.1(d).

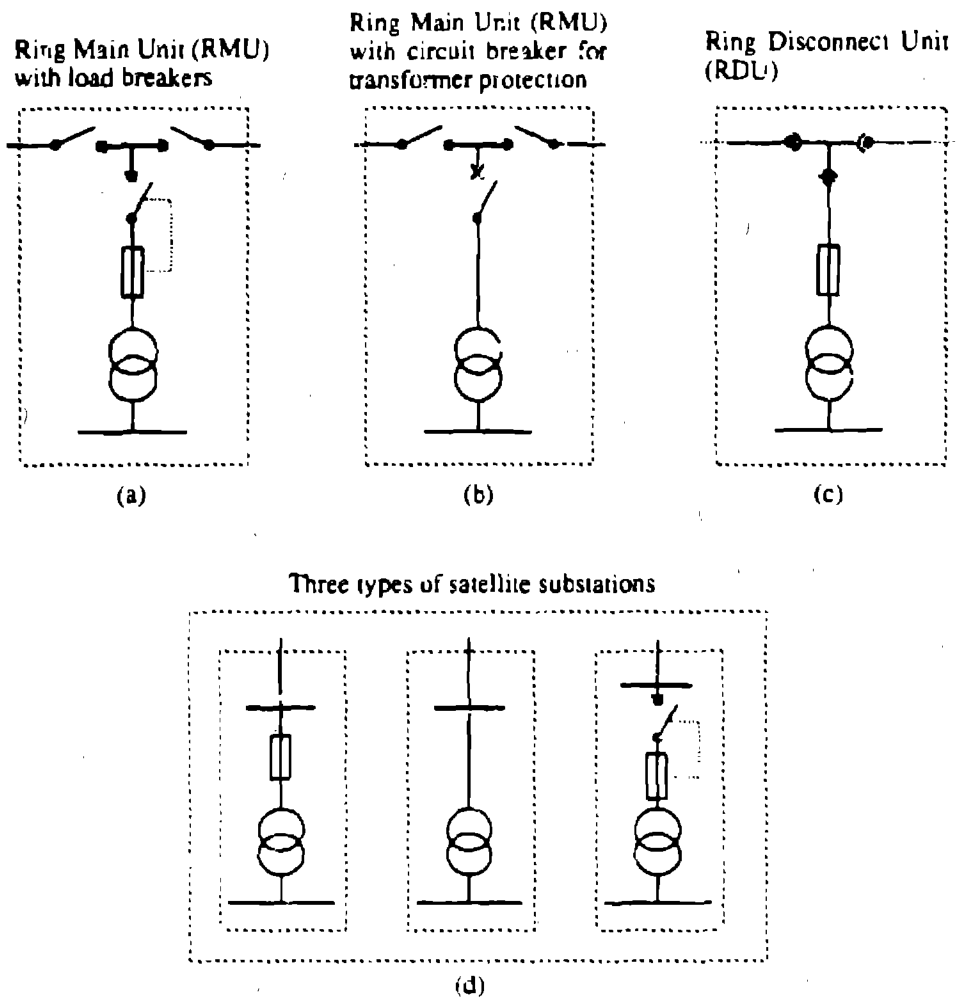
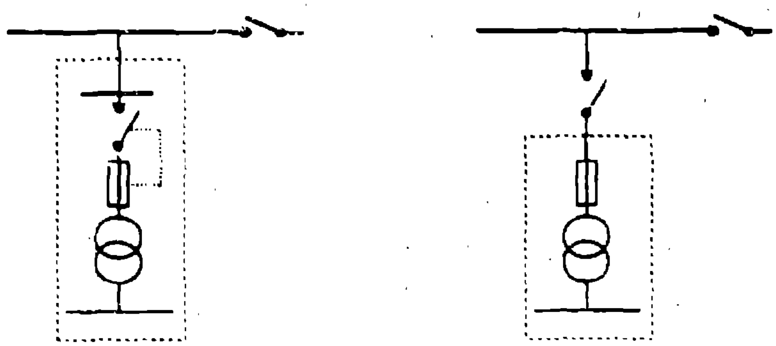


Figure 9.1 Different arrangements in MV/LV substations

9.2.2 Distribution substations situated in the overhead distribution network

Traditionally the MV/LV substations in the overhead distribution network have been pole-mounted. Then the transformer, the fuses and the disconnector were situated on the poles. Earlier the transformer arrangements were either situated on platforms on the poles, or the arrangements were such that the fuses could be replased by help of specially designed insulating tubes operated by the operations engineer from the ground level. The last-mentioned solution is still used for new arrangements in Norway.

During the last 10-15 years small and simple substations situated on the ground near the pole have become very popular. Two different solutions are shown in Figure 9.2.



(a) (b)

Figure 9.2 Two different arrangements for substations situated on the ground in the overhead distribution network.

In Figure 9.2(a) the load breaker, the fuses and the transformer are located in the substation on the ground. In Figure 9.2(b) the load breaker is situated on the pole. The fuses and the transformer are situated inside the ground mounted substation. Both solutions are used today. Sometimes line disconnecting switches mounted in the same pole as the substation arrangement are being used.

9.3 THE MAIN PURPOSE OF THE TRANSFORMER PROTECTION

In the usual arrangement for connecting distribution transformers to the distribution system, there are three main zones that should be protected by the transformers overcurrent or short circuit current protection:

- the region between the transformer and the MV switchgear
- the transformer itself
- the region between the transformer and the LV fuses protecting the LV feeders.

The main purpose of the transformer protection is traditionally to protect the sone between the MV busbar in the MV/LV substation and the fuses on the outgoing LV-cables against overload- or short circuit currents. With the design mostly used today, the main purpose of the transformer protection scheme is as follows:

- The distribution system shall be protected from line lockout in the event of a transformer failure. The transformer protection shall isolate the faulty transformer from the rest of the distribution system by clearing the fault at the transformer location, thus minimizing the number of customers affected.

- The distribution transformer shall be protected from excessive loss of life due to severe overloads or secondary faults, and at the same time permit full utilization of the transformer overload capability.

- The protection scheme shall permit rapid restoration of service in the event of a transformer protective device operation caused by a system disturbance.

- The protection shall insure the safety of the general public and operating personnel by protecting against disruptive transformer tank rupture.

- The time-current characteristic of the primary protection must be selective to the protection of the low voltage side of the transformer.

- The primary transformer protection must be capable of interrupting a wide range of fault currents. The magnitude of these currents is determined by the power distribution system, the location of the fault within the transformer etc.

It is important for the primary current protection to distinguish between the unharmful magnetizing inrush current and internal fault current at transformer energizing. The primary transformer protection must not operate for the primary inrush currents of the transformer.The inrush phenomenon of the transformer is affected by various factors, e.g., switching phase angle of input voltage, residual magnetism, structure of transformer, impedance of power source, load impedance, etc. Smaller transformers will have higher inrush currents, decaying more rapidly, and larger transformers will have smaller inrush, decaying more slowly. An established practice when the transformer protection shall be selected is to choose a protection with a time-current curve placed to the right of a point on $8 - 12 \times i_N$ for 0.1 second for the transformer.

9.4 HOW ARE THE DISTRIBUTION TRANSFORMERS USUALLY PROTECTED TODAY?

There are a great number of possible combinations of fault and overload protective devices which the user can apply, especially to pad mounted distribution transformers. This section will examine some protective devices and protective device combinations

Distribution transformers situated in the cable network have traditionally been protected against primary and secondary faults by a combination of MV fuses (either expulsion fuses or current-limiting fuses) and MV load breakers. The fuses are usually placed between the load breaker and the transformer. The major part of the older substations in service are equipped with open air-insulated load breakers in combination with MV fuses in the transformer circuit. This equipment is very often equipped with automatic trip gear for the load breaker when the striking pin of one fuse releases. There are two main reasons for this combination:

- single-phase operation of the transformer is avoided

- the use of fuse-switch combination extends the area of protection to lower levels than can be provided by fuses alone. When the fuse melts, the fuse striker pin activates the switch and this interrupts the current if it is lower than the transfer current[1].

The service experience with these devices has been fairly good.

During the last few years some manufacturers have introduced secondary switchgear incorporating simple circuit breakers for transformer protection. Then it is usual to equip the circuit breaker with tripping from one or more overcurrent relays. This is sometimes also done when there is a fuse-loadbreaker protection of the transformers.

For larger oil-filled distribution transformers some electricity boards also use gas- or pressure actuated relays to trip the fuse-load breaker or the circuit breaker when internal faults in the transformers occur. To protect the transformers against heavy overloads, temperature sensors for tripping of to the load- or circuit breakers are also used.

Pole mounted transformers are often protected with MV fuses without the combination of automatic trip gear for the load breaker.

9.4.1 Fuse based protection

The fuse, by virtue of its simplicity and low cost, has always been a popular device to provide protection to many items of electrical equipment. Distribution substations are no exception and fuses have been used on both the HV and LV sides of distribution transformers since their inception.

Fuses used as protection have one significant advantage by offering current limiting capabilities when interrupting full rating fault currents, thereby reducing both the fault magnitude and duration. But fuses do also suffer from some disadvantages:

- The elements generate considerable heat, because they have a relatively high resistance. The heat generation may create mounting problems. The use of SF_6 switchgear involves that the fuses not only have to be mounted in air, but to provide a safe compact enclosure they have to be contained in a small space. This will increase the heating of the fuses, and it may be necessary to use fuses with a higher rating.

- The mounting difficulties of the fuses together with SF_6 switchgear may cause problems related to the insulation system, necessarily connected to atmospheric air, particularly where frequent moisture condensation is expected.

- The increased heating of the fuses usually taking place when used together with SF_6 switchgear leads to a deterioration in the discrimination between the HV fuses and the LV fuses [27]. A close match between the HV and the LV fuses is desired in order to give the maximum speed of protection for transformer faults and maintaining sufficient time

1. Also called take-over current.

difference at all fault levels to ensure that the LV fuses always clear LV feeder faults.

- The MV current limiting fuse is subject to the greatest stress when interrupting a current which causes the largest amount of energy to be liberated in the fuse link. This will occur in the low overcurrent zone when pre-arcing time and arcing time are so long that the arc-quenching agent is heated to such an extent that the arc extinguishing properties are reduced.

- Transformer protection by fuses, or by a combination of fuses and switch-disconnectors has distinct shortcomings in the overload range. Faults of low magnitude can not be cleared by HV fuses.

9.4.2 Circuit breaker based protection

The use of oil circuit breakers for the protection of distribution transformers was common in some countries before air-insulated fuse-switch combinations became an attractive solution [2], [27]. In the U.K. cable connected distribution transformers were until the 1960's supplied from oil circuit-breakers with trip coils operated directly from current transformers in the connections to the transformer. In most countries it is still customary to use circuit breakers for the protection of transformers with large power ratings (larger than about 1000 kVA) [2].

As seen in section 9.4.1 the main weakness of the fuse, especially for the current limiting fuse, is a poor performance in the event of low-current fault or overload. As mentioned in section 9.4.1 the introduction of the ring main units applying SF_6 as an insulating medium, the accommodation of the fuses in a manner which maintains the same level of immunity to environmental effects as the switchgear itself, causes some problems [1]. Because of these problems together with the wish to improve protection against low current faults, some manufacturers have during the last few years introduced technical and commercial attractive circuit breaker solutions for transformer protection to the market.

Some general advantages of the circuit breaker as transformer protection are as follows:

- Transformer protection with circuit breakers gives full integration of the SF_6-insulated switchgear.

- The circuit breaker has a low resistance device with losses around 5% of those of a fuse [27].

- The circuit breaker has virtually unlimited current rating for the protection of distribution transformers.

- The circuit breaker will interrupt all currents.

- Microprocessor relays make it possible to cover a wide variety of time/current characteristics and to store energy from the current transformers for the operation of trip coils without an auxiliary supply [2].

- The circuit breaker can be arranged to respond to low-level single phase to earth faults.
- With the circuit breakers the LV side can also be included in the protection zone.

One feature which is seen as a disadvantage for the circuit breaker is it's lack of any fault limiting capability. In the event of a direct, full rated fault there will be substantially less damage limitation than in the case of a current-limiting fuse.

With commercial three-phase inverse overcurrent time microprocessor relays used by ABB in combination with vacuum circuit breakers in the MV switchgear called CTC-V, the total clearing time for the transformer protection system will be as shown in Table 9.1.

Minimum tripping time for the relay	25 ms (+/- 5 ms)
Mechanical opening time for the circuit breaker	40 ms (+/- 5 ms)
Arcing time for the circuit breaker	10 ms
Minimum total clearing time for the protection	75 ms (+/- 10 ms)

Table 9.1 Operation times for a combination of a microprocessor-based overcurrent relay and a vacuum circuit breaker.

9.4.3 Protection against overload and faults between the transformer and the LV-busbars

Traditionally main fuses or circuit breakers between the distribution transformers and the LV-busbars have not been used in Norway. With the traditional switchgears for transformer protection, the MV fuses is the only protection against overload and faults in the sone between the transformer and the fuses on the LV feeders. As mentioned in section 9.4.1, the MV fuses, or a combination of the MV fuses and a load breaker, have distinct shortcomings in the overload range

The LV fuses are usually dimensioned in accordance to the transfer capability of the LV feeders. The LV feeders do usually have a large cross section. If the transformer has more than 3-4 LV feeders, and if the load is shared almost equally between each LV feeder the LV fuses do not give any overload protection of the transformer [55].

In some countries, as for example Holland, it has been common to have LV main fuses between the transformer and the LV busbars [55]. This solution has an improved protection against faults on the LV busbars, and gives an overload protection of the transformer.

In arrangements with larger distribution transformers, some Norwegian users have begun to install a LV circuit breaker between the transformer and the LV busbar. This solution is quite expensive, but it gives a complete overload protection or the distribution transformer.

A solution with a thermal relay in combination with the measuring transformers, usually situated between the distribution transformer and the LV busbars, can be used to trip the MV fuse-loadbreaker when the transformer is overloaded.

9.5 SOURCE PROTECTION OF MV RADIAL DISTRIBUTORS

As seen in Appendix A a radial feeder normally feeds a number of distribution transformers. The feeder itself is normally source protected using overcurrent and earth fault relays in the primary substation. The relatively high impedance of a small distribution transformer may often limit the fault current level of transformer faults or LV terminal faults below that of the normal feeder rating and well below the source overcurrent relay setting. Because of this it has been a common practice to protect the distribution transformers with the local switchgear.

Because distribution transformers have been found to be very reliable, many utilities have started to question if the investment incurred in local switchgears is fully justified.

To reduce the requirements of local switchgear the British Electricity Supply Industry in collaboration with GEC Measurements in the last part of the eighties developed a source protection relay called "Radial Distributor Protection (RDP)" relay [56]. It must be added that this relay is not produced anymore. The RDP relay should be located at the source circuit breaker in the MV substation, and it was said to be able to protect not just the feeder but also all distribution transformers connected to it. Then is should no longer be necessary to provide local protection for the distribution transformers. It is said that the RDP relay was most suitable for application on radial distributors supplying domestic, commercial and light industrial load.

The relay makes use of an incremental technique to detect low level faults in the presence of larger loads. This requires the value of the relay measuring quantity from two cycles earlier to be subtracted from its present value. If the difference is negative it is equated to zero. The resultant increment is then compared with the setting to determine that a fault condition exists. When a fault is determined, the process of updating the reference condition is suspended so that the value immediately prior to fault inception is retained until either the relay trips and clears the fault, or the fault is cleared elsewhere, perhaps by an LV fuse link operation.

One problem with source protection of distribution transformers is the alteration in the configuration of the radials each time the MV network is recoupled.

The incremental technique used is based on positive phase sequence and negative phase sequence values. It is said that the unbalanced faults can be detected by the negative phase sequence values, and the three phase faults are detected by the positive phase sequence detector [56]. Some of these relays are in use by various supply authorities in the U.K.

The idea of the source protection relay is very interesting, but it has been outside the scope of this thesis to study the details.

9.6 COMPARISON OF DIFFERENT TYPES OF DISTRIBUTION TRANSFORMER PROTECTION

The discussion in this section will be based on the experiments with internal short circuits between turns in the MV windings described in chapter 7, the experiments with internal power arcs described in chapter 8 and chapter 3 about experiments described in the literature.

9.6.1 Discussion of protection of the transformers based on the full scale tests at "Munkvoll" with short circuits between turns or layers in the medium voltage coil

The experiments are described in chapter 7. Tests with internal short circuits between neighbouring turns or layers in the MV winding on one limb of three phase 300-315 kVA transformers were carried out. When two neighbouring turns were short-circuited, it took about 1.7-3.2 seconds from the short circuit was established until the fault developed further. This time is of cause dependent on many factors, such as winding construction, the induction in the transformer core (voltage per turn), cooling conditions, contact resistance at the place where the two turns are short-circuited etc. From the four tests with short circuits between neighbouring turns is was seen that the line currents increased only by a small fraction. In practice it is almost impossible to detect a short circuit between two neighbouring MV turns in a loaded distribution transformer by a measurement of the line current.

Table 9.2 gives a survey of expected operation times for different kinds of protection of the transformers in the tests. The times are measured from the time the short circuits between two neighbouring turns developed further.

There are large differences in the time-current characteristics for the fuses from one manufacturer to another. It is important to realize that the times for the fuses given in Table 9.2 are the minimum melting time for the fuses, and not the total clearing time. The total clearing time for the fuses with the existing currents in the tests would have been considerably larger than the melting time for the fuses. With the currents that appeared in these tests, the load breaker would have cleared the fault after it was triggered of the striking pin of one fuse. The mechanical opening time for the load breaker can be about 100 ms or more, and the arcing time for the load breaker can be about 10 ms or more.

Overcurrent time relays, gas- or pressure actuated relays can be used in combination with a fuse-load breaker or a circuit breaker. From the tests it is seen that the gas relays operated very satisfactorily. The tripping times for the overcurrent time relay compared to the minimum melting times for the fuses shows that in some cases the overcurrent time relay would have detected the fault currents faster than the fuses and vice versa. But theoretical it is possible to design microprocessor relays with time/current characteristics for faster tripping in the overload situation.

Test no.	1	2		3	4	5
		1st test	2nd test			
Fuse, 25A Manufacturer A(1) [s]	5.5	No oper. first 29 s.	0.35	No oper. expected	1.2	No oper. first 65 s.
Fuse, 40A Manufacturer A(1) [s]	No oper. first 24 s.	No oper. first 29 s.	7	No oper. expected	25	No oper. first 65 s.
Fuse, 25A Manufacturer B(2) [s]	0.4	No oper. first 29 s.	0.05	No oper. expected	0.12	0.16
Fuse, 40A Manufacturer B(2) [s]	No oper. first 24 s.	No oper. first 29 s.	0.3	No oper. expected	1.4 (*)	35 (*)
Fuse, 40A Manufacturer C(3) [s]	No oper. first 24 s.	No oper. first 29 s.	0.6 (*)	No oper. expected	4 (*)	No oper. first 65 s.
Fuse, 40A Manufacturer D(4) [s]	No oper. first 24 s.	No oper. first 29 s.	No oper. expected	No oper. expected	No oper. expected	No oper. first 65 s.
Overcurrent time relay Manufacturer E(5) [s]	2	No oper. first 29 s.	0.35	No oper. expected	0.75	No oper. first 65 s.
Gas-relay [s]	0.6	No oper. first 29 s.	-	No oper.	2.24	2.74
Pressure-relay [s]	-	-	-	-	3.61	No oper. first 65 s.

(1) Minimum melting time for the current limiting fuses. (ABB type CEF).
(2) The average value of the minimum melting time for the current limiting fuses. (SIEMENS type 3GA, not produced anymore).
(3) The average value of the minimum melting time for the current limiting fuses. (SIEMENS type F139).
(4) The average value of the minimum melting time for the current limiting fuses. (SIEMENS type 3GD).
(5) The minimum tripping current of the three-phase inverse overcurrent time relay is 25.0 A.
(*) The current is less than the guaranteed clearing current for the fuses.

Table 9.2 Expected operation times for different protections if they were used during the tests with short circuits between turns.

9.6.2 Discussion of protection of the transformers based on the full scale tests at "NEFI" with internal power arcs between two phases in the transformers

The experiments are described in chapter 8. Tests with internal power arcs between two

neighbouring phases on the MV side of the transformer were carried out on distribution transformers with rating from 50 to 500 kVA. The tests showed that with this kind of fault it is very important to reduce the arcing time to a minimum to avoid explosion or cracking of the transformer tank.

It is clear that current limiting MV fuses are very effective as transformer protection with this kind of fault, thanks to their ability to limit the duration and amplitude of the high short-circuit currents which may cause explosions.

The operating time of a modern circuit breaker would seem incompatible with the transformer protection requirements against internal power arc faults of this type with high short-circuit power levels. The same conclusion is also drawn in many other research works presented in the literature. But it is very important to notice that an instantaneous formation of a power arc in oil is now questioned, without any previous history of the fault development. This type of fault with sudden, high magnitude faults does practically almost never occur.

9.6.3 Discussion of protection of transformers based on experiments with internal faults described in the literature

The discussion will be based on experiments described in chapter 3, and is a result of assessments done by the author of this thesis.

Protection of the transformers with internal short circuits between turns in the MV or LV coils tested and described in [39]:

The tests referred to were described in section 3.6. The current development in the tests is given in Table 3.2 on page 31 and Table 3.2 on page 31. The filled arrows in the time lapse for each test show when it is expected that correct dimensioned current limiting fuses (type CEF manufactured by ABB) would have cleared the fault current. The open arrows show when it is expected that a commercial type of an inverse overcurrent time relay together with a circuit breaker (used by ABB) would have cleared the fault current. The minimum tripping current for the relay is set to two times the rated primary current of the transformer. The minimum operation time for the combination of the relay and the circuit breaker is expected to be as shown in Table 9.1, and is set to be 75 ms.

In five of the tests the transformer tank cracked (test no. 1, 2, 6, 10 and 11). The results show that it is expected that a correct dimensioned current limiting fuse would have prevented rupture of the transformer tank in all the tests. It is also expected that the inverse overcurrent relay together with the circuit breaker would have prevented rupture of the transformer tank in 4 of the 5 tests. In test no. 2 it is uncertain if the overcurrent relay and the circuit breaker would have disconnected the transformer fast enough to prevent tank rupture.

In test no. 11 it is seen that the inverse overcurrent relay with a minimum tripping current of two times the rated primary current for the transformer, together with the circuit breaker, would have disconnected the transformer more than 9 hours before it exploded. If the fault current had been less than two times the rated current for the transformer in the period $t = -33000$ s to

$t = -840$ s it is expected that the relay and the circuit breaker would have disconnected the transformer about 220 s earlier than the fuses.

In two of the tests (test no. 4 and 8) neither the fuses nor the inverse overcurrent relay and circuit breaker would have detected and disconnected the faulty transformers.

In [39] it is said if the transformers tested had been equipped with Buchholz relays, the relays would have tripped a circuit breaker or a fuse-load breaker fast enough to get the transformer disconnected before the transformer tank cracked.

Protection of transformers with insulation faults between MV-phases:

The discussion is based on results described in section 3.6.1.

Tests with internal power arcs between two phases downstream from the MV terminals indicated that the fault currents have to be interrupted very fast to avoid transformer explosions [38], [39]. For this very rare type of fault, current limiting fuses are probably the best type of protection which exists, due to their ability to limit the duration and amplitude of the short circuit currents.

9.7 PROCEDURES DURING REENERGIZING OF TRANSFORMERS DISCONNECTED BY THEIR PROTECTION

Operating personnel may find a MV fuse blown but no other visible indication of damage. The operating personnel may attempt, and in some cases it may also be accepted practice, to replace the fuse, perhaps of a higher rating, and reclose the circuit. Even if the first fuse operation was uneventful, the second may not be if the system can deliver enough energy to the fault. The result may be catastrophic failure with serious consequences to the operating personnel and general public (perhaps nearby spectators).

The approach is the same if the transformer for instance is protected by an overcurrent relay and a circuit breaker.

It is absolutely essential for the electricity boards and the legislative organizations to think through this problem, and give clear rules and instructions how to reenergize transformers after its protection has disconnected the transformer.

9.8 CONCLUSIONS

- The MV switchgear of a substation has the following functions:
  - provide section points for the system that can be closed or opened with the system in service.
  - isolate faulty cables or lines.
  - protect and isolate the distribution transformer when required.

- The main part of the older substations in service is equipped with open air-insulated load breakers in combination with MV fuses in the transformer circuit.
- During the last 5-8 years a new generation of environmental proof units applying SF_6 as an insulating medium have increased their share of the market.
- The most used MV switching and isolating arrangement in the cable network is the ring main unit (RMU).
- Traditionally, load breakers have been used for the MV feeders, and load breakers in combination with MV fuses have been used as transformer overcurrent protection.
- The main purpose of the distribution transformer overcurrent protection scheme is as follows:
  - insure the safety of the general public and operating personnel by protecting against disruptive transformer tank rupture.
  - protect the distribution system from line lockout in the event of a transformer failure.
  - protect the transformers against overloads and secondary faults.
- Current limiting MV fuses as transformer protection have one significant advantage in that they are current limiting when interrupting full rating fault currents. Some disadvantages of such fuses are:
  - the elements generate considerable heat
  - mounting and integration problems of the fuses in the SF_6 switchgear.
  - transformer protection by fuses, or by a combination of fuses and switch-disconnectors has distinct shortcomings in the overload range.
- Because of the problems with the MV fuses, and the wish to improve protecting against low current faults, some manufacturers have introduced technical and commercial attractive circuit breaker solutions for transformer overcurrent protection into the market. The main disadvantage for the circuit breaker is the lack of fault limiting capability. Some general advantages of the circuit breaker as transformer protection are:
  - transformer protection with circuit breakers gives full integration of the SF_6 insulated switchgear.
  - the circuit breaker has low heat generation.
  - almost unlimited rating for protection of distribution transformers.
- Use of source protection of MV radial feeders located at the source circuit breaker is very interesting, but one problem with source protection of distribution transformers is the alteration of the configuration of the radials each time the MV network is recoupled. Source protection of distribution transformers is not studied in this thesis.
- Traditionally main fuses or circuit breakers between the distribution transformers and the LV busbars have not been used in Norway.
- Use of main LV fuses between the transformer and the LV busbars give an improved

protection against faults on the LV busbars, and gives an overload protection of the transformer.

- Use of LV circuit breaker between the transformer and the LV busbars gives a complete overload protection of the distribution transformer.
- Use of thermal relays, placed between the transformer and the LV busbar, can be used to trip the MV fuse-loadbreaker when the transformer is overloaded.
- Tests with internal power arcs between two phases on the MV side of distribution transformers have shown that with this type of fault it is very important to reduce the arcing time and the arcing energy to a minimum to avoid cracking o explosion of the transformer tank. This result is also confirmed in the literature. With an instantaneous formation of a power arc in an oil filled transformer, without any previous history of the fault development, it is agreement about that the best kind of protection is MV current limiting fuses, due to their ability to limit the duration and amplitude of the high short circuit currents. But it is also confirmed in the literature that this kind of fault does almost never occur.
- Tests with internal short circuits between neighbouring turns in the MV windings of the transformer showed that the line currents quite fast reach values that can easily be detected by specially designed overcurrent relays. Depending on the time-current characteristic of MV current limiting fuses, the fault currents may also be detected by such fuses. There are large differences in the time-current characteristics for MV fuses from one manufacturer to another. If fuses are used as transformer protection it is important to choose a fuse with a favorable time-current characteristic in the overcurrent range of the transformer. In this range there are large differences between fuses from one manufacturer to another.
- From the tests on Munkvoll, described in chapter 7, it was seen that the gas actuated relays (Buchholz-type) operated very satisfactorily and fast both for the tests of the transformers with conservator and for the transformers of the hermetically-sealed type. For the tests described in [39] it is also concluded that Buchholz relays would have tripped a circuit breaker or a fuse-load breaker fast enough to get the transformer disconnected before the transformer tank cracked.

10 DISCUSSION

The main objectives of this thesis were to investigate different mechanisms of internal faults in distribution transformers, and to better understand the physical and electrical behaviours of internal faults in distribution transformers. It was also an objective to study the effectiveness of different overcurrent protection schemes in response to different kinds of transformer faults.

A literature search for the basic causes of failures in distribution transformers was performed. In the literature, there is general agreement that the great majority of internal failures in distribution transformers starts as insulation faults and short circuits between neighbouring turns or layers in the windings. When a distribution transformer has been exposed to an internal winding failure, it is as a rule very difficult to determine what has caused the failure, since all evidence is eliminated by the very nature of the breakdown.

In section 2.3 it was found that insulation failures can be triggered by any of the following mechanisms:

- Thermal failures
- Mechanical stresses
- Electrical failures
- Aging processes.

In overhead systems, the fault rate for distribution transformers is 10-20 times higher than in cable connected systems. The fault rate for transformers in an overhead system is very dependent on the frequency of thunderstorms and lightning. It is clear that the major part of the failures in distribution transformers in overhead systems is triggered by surge voltages caused by lightning.

Transformers installed in underground cable networks are normally not exposed to surge voltages caused by lightning. It is therefore likely that some of the other failure mechanisms mentioned in section 2.3 are more relevant for distribution transformers installed in the cable network.

The great majority of the short circuits between turns are said to be progressive. Electrical contact between two adjacent turns of wire will cause a high current to flow through the turn involved. The local heat generation then leads to further damage and the fault may develop and involve more turns.

With only a few turns short-circuited, the increase of the line current is relatively small. The low magnitude of currents drawn from the primary lines is due to the high ratio of total primary turns to short-circuited turns. The tests with short circuits between two neighbouring turns, described in chapter 7, showed that for the transformers with secondary load of about one-half of rated current, the primary line currents increased by only 13-17% when only one MV turn was short-circuited. In practice, it is almost impossible to detect a short circuit between two neighbouring MV turns in a loaded distribution transformer by a measurement of the line current. The time from establishing the short circuit between two neighbouring turns until the fault developed further was measured to

be 1.75-3.2 seconds. This time was on the same order as the tests on the single-phase transformer model described in chapter 5. As the damage expands to larger parts of the winding, the winding impedance decreases very fast and the primary current increases. The degree of increase depends on factors such as the construction, connection and the amount of cooling provided by the oil. Based on measurements and calculations for the single phase transformer model described in section 5.9 and section 5.10, it was found that the average temperature in the short-circuited turns was about 600-700 °C at the time when the faults developed further. Calculations predicted this temperature to be higher than in tests with short circuits between layers. One possible reason for this is described in section 5.10.3.

In tests described in the literature (section 3.6), great variations were observed in how fast MV insulation failures develop further. From the tests described in [39] it seemed as if a winding fault in transformers with layer windings evolved more quickly than in transformers with crossover coils. This was not observed in the full scale tests at "Munkvoll", described in chapter 7.

Contrasts between delta and star-connected transformers were studied. For transformers designed for the same rated power and volts per turn, the cross-section of the wire in a star-connected transformer will usually be $\sqrt{3}$ times larger than for the wire in a delta-connected transformer. The number of primary turns in the delta-connected transformer is $\sqrt{3}$ times larger than in a similar star-connected transformer. If two neighbouring turns are short-circuited, the power loss in the short-circuited turn in the star-connected transformer will be $\sqrt{3}$ times larger than in the delta-connected transformer. When the number of short-circuited turns increases, the current in the short-circuited turns will be about constant for the delta-connected transformer. The star-connected transformer with an unearthed neutral allows the neutral potential to float with respect to ground. This reduces the voltage at the short circuit when the number of short-circuited turns increases. This is shown theoretically in Figure 4.8 on page 50. The measurements from the tests with a short circuit between turns gave the same results (Figure 7.19 on page 135). Because of this, the increase of the primary line currents will be larger for a delta-connected transformer than for a star-connected transformer as the number of short-circuited turns is increasing.

The reactances in equations (4.61), (4.83) and (4.106) can not be calculated analytically. But to get an estimate of the theoretical maximum line currents which can arise with a given number of turns short-circuited, the reactances included in the equations mentioned above can be set to zero. It is clear that this will give estimates for the line currents which are far too large, especially when the primary of the transformer is star-connected and the number of short-circuited turns is increasing.

Gases are generated by heat decomposition of oil or oil-impregnated materials when faults due to local heating, partial discharge, or arc discharge occur in the transformer. With increasing temperature, the proportions of unsaturated hydro-carbon compounds increase. If solid insulating materials are affected, the amount of carbon monoxide (CO) and carbon dioxide (CO_2) also increases. The major gas produced during partial discharges in oil is hydrogen (H_2) and methane (CH_4). High density electrical discharges pyrolytically break down the oil almost completely to its basic chemical components. In addition to carbon, which disperses evenly throughout the oil in

the form of extremely fine particles, typical gases given off are hydrogen (H_2) and acetylene (C_2H_2).

Tests[1] with internal faults in the windings of distribution transformers have shown that the fault can develop further and include local heating, partial discharges and internal arcs. It is clear that a variety of gases may be produced with a fault in the windings of an oil-filled distribution transformer. The main gases produced during different kinds of faults are described in Table 6.1 and Table 6.2 on page 100. The rate of evolution of gas is proportional to the magnitude of the fault, and the composition of the gases is related to the type of fault. The gases and mixtures of gases are flammable and explosive, as well as non-condensable. From Table 6.3 on page 101, it is seen that the explosion limits (in % by volume in air) for some of the gases are wide, and the ignition temperatures are relatively low.

A very large volume of gas is produced in a short time from a normal type of arc in mineral transformer oil. The tests mentioned above have also shown that local overheating of short-circuited turns [illegible] transformer can lead to vigorous gas evolution from the oil. The principle of using a gas-actuated relay to detect internal faults in oil-filled transformers is old and familiar. But this kind of relay has not been in common use on distribution transformers, although it has been commercially available both for transformers of the open system with conservator, and for transformers of the hermetically-sealed type. The full scale experiments with short circuits between turns in the medium voltage coil described in chapter 7, showed that this kind of gas actuated relay (Buchholz type) operated very satisfactorily and fast for this kind of faults[2].

Appendix B gives a description of an internal fault in a distribution transformer with subsequent explosion of the substation. It is likely that the destruction of the MV coils was caused by internal short circuits between neighbouring turns or layers. The internal fault in the MV winding caused severe heating of parts of the MV coil. There also may have been internal arcs in the MV winding. The severe heating and the discharges and arcs caused decomposition of the oil into different highly heated gases, oil vapour and oil mist. The hot gases and the hot oil mist flowed through the oil and through the conservator into the air in the substation. There was no ventilation in the substation, and it is supposed that after some time a large volume of flammable and explosive gas mixtures and oil mist collected inside the substation. It is likely that the gases and oil mist flowing out from the conservator had reached the self-ignition temperature, which may be as low as 330-350 °C. It also seems to be apparent that a gas actuated relay would have operated very quickly for this fault. The signal from this relay could have been used to trip the primary load-breaker or to open a circuit breaker.

The results from the tests on "Munkvoll", described in chapter 7, showed that a short circuit between two neighbouring turns could develop in two different directions:

1. The short-circuited turn melted off, but contact was probably established between two turns, whose insulation varnish was damaged by the high temperature in the short-

1. Tests described in the literature, chapter 3, and tests described in chapter 5 and chapter 7.
2. In the tests with short circuits between neighbouring turns the gas actuated relays operated 0.5-2.7 seconds after the fault developed further.

circuited turn. The transformer appeared to work normally after this.
2. The fault developed further, and other turns were involved in the short circuit.

In one of the tests the fault was intermittent[1].

The tests described in the literature [39], section 3.6, showed that a short circuit between turns may develop into a full short circuit. There were great variations in how quickly the MV insulation failure developed further. It must be noted that none of these tests started as short circuits between only two neighbouring turns. In all the tests with short circuits between MV turns described in [39], larger parts of the MV winding was short-circuited.

For an instantaneous formation of a power arc inside an oil filled distribution transformer, without any previous history of the fault development, current limiting MV fuses are very effective as transformer protection, thanks to their ability to limit the duration and amplitude of the high short-circuit currents which may cause explosions. This was also stated by the tests described by [39] in section 3.6.1, and by the tests described in chapter 8. But this type of sudden, high magnitude faults will almost never occur in practicality.

Tests[2] with internal short circuits between turns in the MV windings of the transformer have shown that usually the line currents quickly reach values which may be detected by specially designed overcurrent relays. Depending on the time-current characteristic of MV current limiting fuses, the fault currents may also be detected by such fuses.

As mentioned earlier, the tests described in chapter 7 showed that gas-actuated relays operated very satisfactorily and quickly, both for the transformers with conservator and for the transformers of the hermetically-sealed type. For the tests described in [39], section 3.6, it is also concluded that Buchholz relays would have tripped a circuit breaker or a fuse-load breaker quickly enough to disconnect the transformer before its tank cracked

1. The test on transformer no.5, described in section 7.4.5
2. Tests on "Munkvoll", described in chapter 7, and tests described in the literature, chapter 3

11 CONCLUSIONS

- The fault rate for distribution transformers in cable networks is less than 0.1 fault per 100 transformer years[1]. The fault rate for distribution transformers in overhead line networks is of course very dependent on the frequency of thunderstorms and lightning. Based on statistics presented by EFI in [24], the average fault rate for distribution transformers in overhead line networks in Norway in the period 1981-91 was 1.85 faults per 100 transformer years.

- The objectives of overcurrent and fault-current protection of distribution transformers are not based on economic or reliability considerations. Instead, the goal is to ensure the safety of the general public and operating personnel by protecting against explosions or violent transformer tank rupture.

- The great majority of internal failures in distribution transformers starts as insulation faults and short circuits between neighbouring turns or layers in the windings. The insulation failures can be triggered by factors such as thermal failures, mechanical stresses, electrical failures or aging processes. Failures in distribution transformers located in overhead networks are mostly caused by lightning overvoltages.

- Electrical contact between two adjacent turns of wire will cause a high current to flow through the turns involved. When relatively few turns are short-circuited, a large current flows in the short-circuited turns, while relatively low currents are drawn from the primary lines. The low currents are due to the high ratio of the number of primary turns to the short-circuited turns. With only one MV turn short-circuited, the line current caused by the short circuit will usually be considerably less than the rated primary current. The local heat generation then leads to further damage, and the fault may involve more turns. When the damage extends to larger parts of the winding, the primary current increases. This progression depends on such factors as transformer connection, winding construction and the amount of cooling provided by the oil. Tests[2] with short circuits between neighbouring MV turns in distribution transformers have shown that when the fault develops further, the line currents quickly reach values several times that of the rated primary current for the transformer. The star-connected transformer with unearthed neutral allows the neutral to float with respect to earth. This reduces the voltage across the faulty phase winding when the number of short-circuited turns increases. Because of this, the increase of the primary line currents will be larger for a delta-connected transformer than for a star-connected transformer when the number of short-circuited turns increases.

- Tests with internal faults in the windings of mineral-oil-filled distribution transformers have shown that faults can develop further and include both local heating, partial discharges and internal arcs. A variety of gases can be produced with a fault in the windings in an oil-filled distribution transformer. In the case of local heating, methane (CH_4), ethylene (C_2H_4) and propylene (C_3H_6) are produced in large amounts. Hydrogen (H_2) and acetylene (C_2H_2) are produced in large amounts for arc discharges. If solid insulating materials are affected, large

1. This is based on fault statistics from Germany, Holland and the United Kingdom.
2. The tests described in chapter 5 and 7.

amounts of carbon monoxide (CO) and carbon dioxide (CO_2) will be generated. Heating of oil will also create oil vapour. The gases and mixtures of gases are flammable and explosive as well as non-condensable. The explosion limits for some of the gases are wide, and the ignition temperatures are relatively low. The explosion limits for oil mist are wide, and the self-ignition temperature for oil mist can be as low as 330-350 °C.

- Tests with internal short circuits between neighbouring turns in the MV windings of the transformer showed that the line currents developed into values that sometimes may be detected by specially designed overcurrent relays. Depending on the time-current characteristic of MV current limiting fuses, the fault currents may sometimes also be detected by such fuses, but there are large differences in the time-current characteristics for MV fuses from one manufacturer to another, especially in the overcurrent range. Consequently, adequate overcurrent protection against the most common type of internal faults in distribution transformers can not be achieved, neither with the implementation with primary circuit breaker and commercial overcurrent relays, nor with the fuse-loadbreaker combination.

- Tests with internal short circuits between turns have shown that gas-actuated Buchholz relays operate very satisfactorily and quickly both for transformers with conservator and for hermetically-sealed transformers. Used together with a primary circuit breaker or a fuse-loadbreaker combination, gas actuated relays seem to be the best safety arrangement for the most common type of fault in distribution transformers, namely short circuits between neighbouring turns or layers of turns in the windings.

- Tests with internal power arcs between two phases on the MV side of distribution transformers have shown that with this type of fault it is very important to reduce the arcing time and the arcing energy to a minimum in order to avoid cracking or explosion of the transformer tank. With an instantaneous formation of a power arc in an oil-filled transformer, without any previous history of the fault development, it is agreed that the best kind of protection is MV current limiting fuses. But it is also confirmed in the literature that this kind of fault almost never occurs. Therefore, it is clear that long arcs drawn directly in oil probably represent a worst case rather than the usual internal fault. A slowly evolving fault may eventually lead to such arcs as a worst case.

- Traditional protection in Norway, using a combination of MV fuses and a load breaker, has distinct shortcomings in the overload range. In addition to existing schemes, it is recommended to have protection against overload and faults between the transformer and the LV busbar. Such protection can be accomplished in different ways:

  - Use of LV main fuses between the transformer and the LV busbar.
  - Use of LV circuit breaker in combination with suitable overcurrent- or thermal relays between the transformer and the LV busbar.
  - Use of suitable overcurrent- or thermal relays between the transformer and the LV busbar to trip the primary breaker (either a fuse-loadbreaker or a circuit breaker).

Appendix A A BRIEF SURVEY OF THE DESIGN OF DISTRIBUTION NETWORKS

In designing distribution networks, supplies can be provided to different areas of the system in a variety of ways, depending on the load density and system voltage level. The following conditions are common for the different network configurations:

- The distribution network can be supplied from one ore more HV/MV substations.
- Each MV/LV substation can be supplied in one or more ways.
- The networks can be sectionized.

Examinations have shown that the availability is almost not affected by the network configuration, when the MV/LV substation is supplied in at least one alternative way [57]. In this chapter some types of different network configurations will be shown.

Ring and mesh systems are almost always operated split with normally open points.

Most of the information in this chapter is described in [57] and [58].

A1. Radial system

The purely radial networks without the facility of backup interconnection are in common use particularly in the countryside, and is usually designed for a topography with scattered population, see Figure A.1. Rural situations often involve long distribution networks separated by areas with little or no habitation. The rural networks are usually overhead lines, and the reliability is sometimes low. The radial networks are characterized by having many small MV/LV substations, and they are very often of pole-mounted type. The rated power of pole-mounted transformers is seldom more than 200 kVA.

During the last few years is has become more common to replace the pole-mounted arrangements by pad-mounted MV/LV substations. In these substations transformers with ratings above 315-500 kVA are seldom used. The simple pad-mounted MV/LV substations are usually equipped with current limiting MV fuses and load breakers

To increase the reliability the radial networks are sometimes equipped with circuit breakers in the radials.

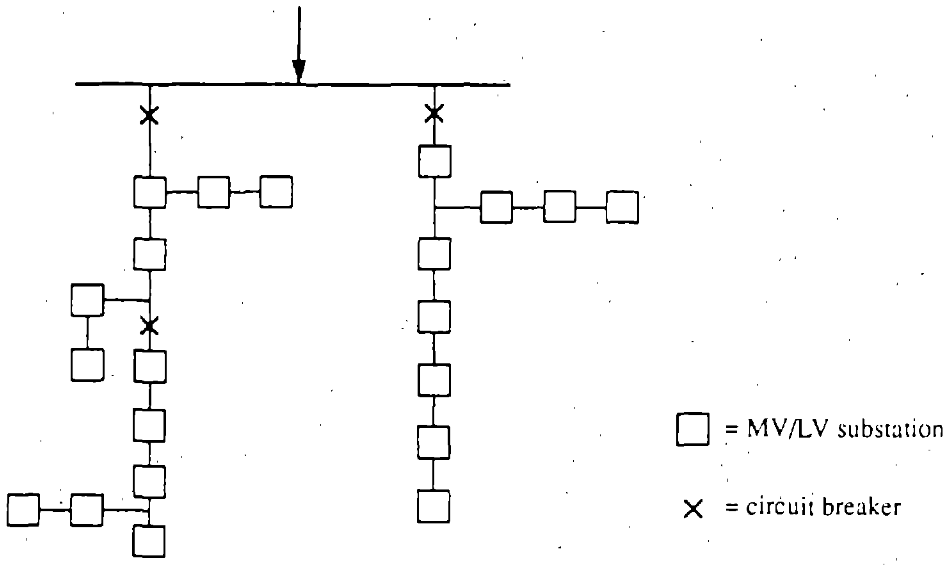


Figure A.1 A schematic description of a radial distribution network.

A2. Mesh networks

Mesh networks are the most commonly used cable network system in Norway. The mesh structure is often a result of a gradual extension with new substations and cable connections, without any restructuring of the network. The network is often supplied from more than one HV/MV transformer station. The mesh networks are almost always operated as radial networks.

The MV/LV substations can usually be supplied in many different ways. Each substation is usually equipped with 2-4 load breakers for MV cable feeders. The transformers are usually connected to the system through load breaker switches in series with current limiting fuses. A mesh network is shown in Figure A.2.

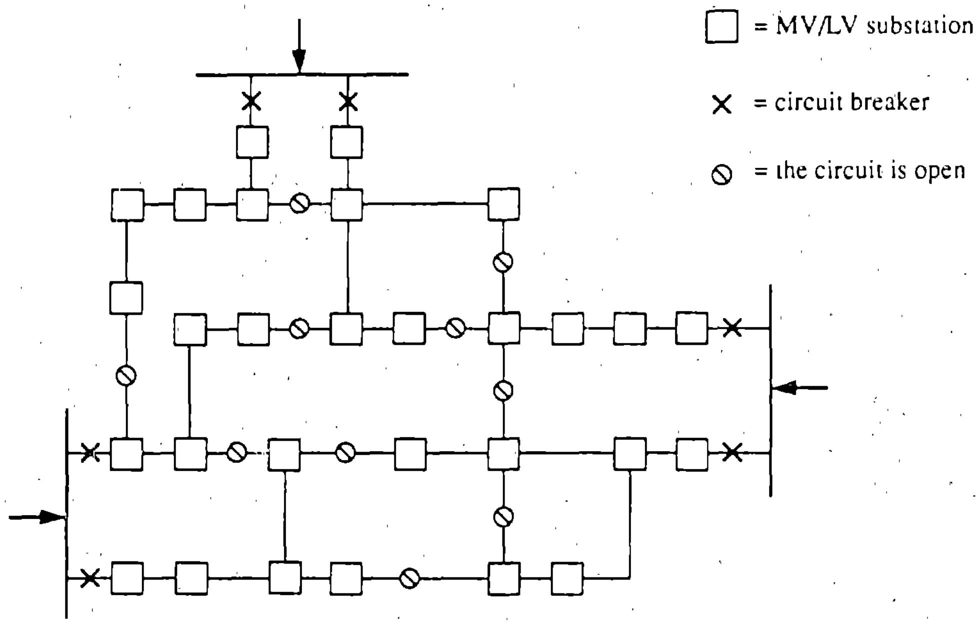


Figure A.2 A schematic description of a mesh network.

A3. Open loop networks

These networks form simple loops from one single HV/MV substation. Under normal operating conditions the network is operated as a number of radial feeders.

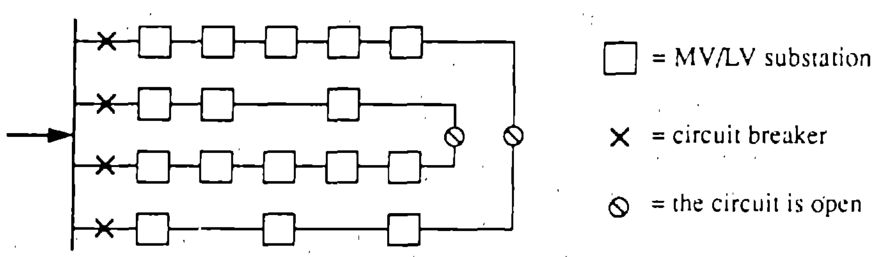


Figure A.3 A schematic description of open loop networks.

To attain full auxiliary supply, each of the outgoing cables must be designed to supply the whole loop network alone. The networks shown in Figure A.3 is often used in other European countries.

In Oslo and Bergen, modified open loop networks with a separate auxiliary cable have been in use for many years. See Figure A.4.

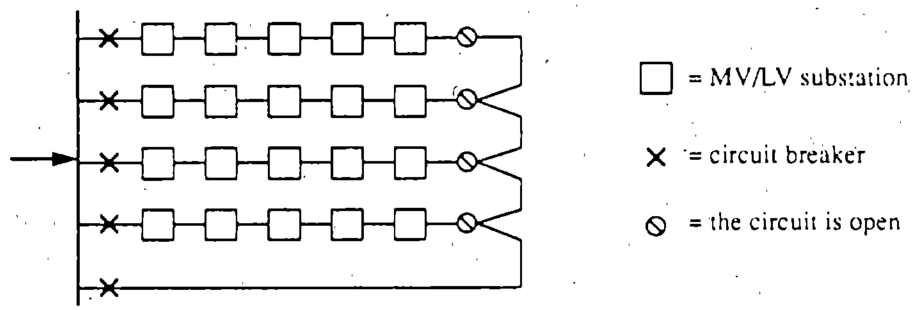


Figure A.4 A schematic description of open loop networks with a separate auxiliary cable.

The network was designed so that each of the main cables could be 100% loaded. The auxiliary cable was designed to give full auxiliary supply when one of the main cables failed. Today it is not economical to have full load on the cables.

A4. Link arrangement

This is in principle a single open loop network where the ring ends up in another HV/MV transformer station. This network is also usually operated as radial feeders. The open points are closed when one of the infeed substations is out of service. Each of the cable feeders must be designed to supply 100% of the load alone.

The possibility of feeding from two or more HV/MV transformer stations reduces the requirement of having auxiliary transformer capacity in the HV/MV transformer station. The arrangement is shown in Figure A.5.

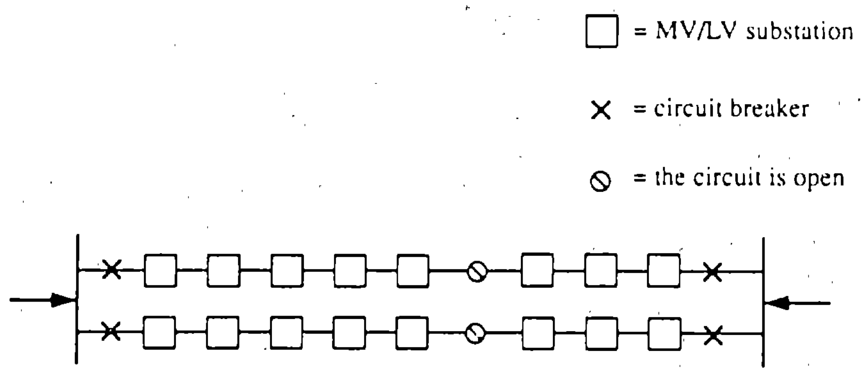


Figure A.5 A schematic description of a link arrangement.

A5. Networks using satellite substations

This is networks which include small "satellite MV/LV substations" without MV breakers. These satellite substations are supplied from larger MV/LV substations. Each supporting circuit from the larger MV/LV substation is equipped with a breaker and a kind of transformer protection (usually CL-fuses). The combination of a few large MV/LV substations and many satellite substations reduces the investment cost of the distribution network. An example of a network is shown in Figure A.6.

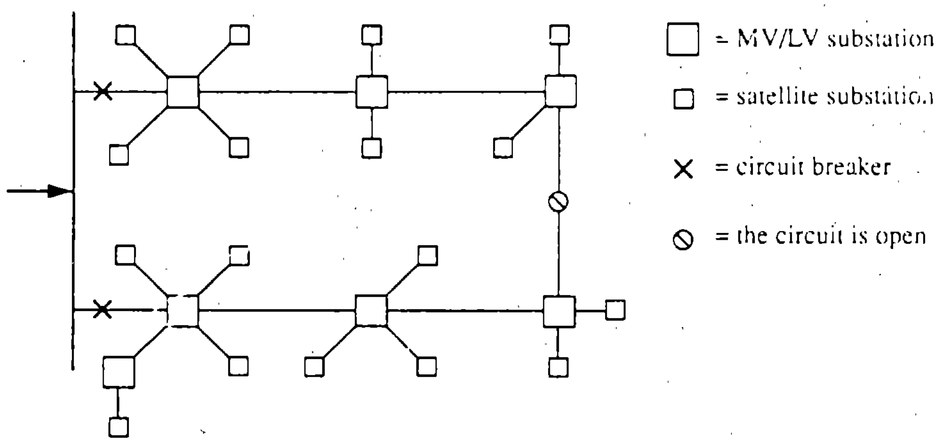


Figure A.6 A schematic description of a network using satellite substations.

This network will have reduced losses compared to conventional networks, because the satellite substations can be located closer to the consumers.

This solution have been used in Bergen for many years. In one area about 2000 flats are supplied from 7 large MV/LV substations and 45 satellite substations. The experience with this solution is said to be very satisfactory [57].

A6. Conclusions

- Types of distribution networks:
  - The purely radial networks without the facility of backup interconnection are in common use particularly in the country. The rural networks are usually overhead lines, and the reliability is sometimes low.
  - It is expected that the solution with satellite substations will be very popular in the future, due to the reduction in investment cost of the distribution network and reduced losses[1] compared to conventional networks.

- The MV switchgear of a substation has the following functions:
  - provide section points in the system for closing or opening with the system in service.
  - isolate faulty cables or lines.
  - protect and isolate the distribution transformer when required.

1. Reduces losses because the satellite substations can be placed closer to the consumers.

Appendix B INTERNAL FAULT IN A 100 KVA TRANSFORMER WITH SUBSEQUENT EXPLOSION IN THE SUBSTATION

In april 1993 a 12/0.23 kV substation in the distribution network belonging to Skiensfjordens kommunale kraftselskap (SKK) in Norway disintegrated. The substation (SIEMENS F82) was equipped with a SF_6 insulated 12 kV switchgear and a 100 kVA mineral-oil insulated Yyn0 distribution transformer. The transformer was protected by a combination of a SF_6 load breaker and current limiting MV fuses (type "CEF-25" manufactured by ABB).

Examination of the SF_6 insulated switchgear after the accident showed that the SF_6 compartment had not exploded or cracked. Then it was apparent that the SF_6 compartment had nothing to do with the explosion of the substation.

Because of necessary routine work on the MV line supporting the MV/LV substation, the line had been disconnected for about one hour earlier that day. The line was reclosed about 3.5 hours before the explosion. About 5 minutes before the explosion, a customer called SKK and reported irregular voltage in the LV network. Figure B.1 shows a picture of the substation after the explosion.

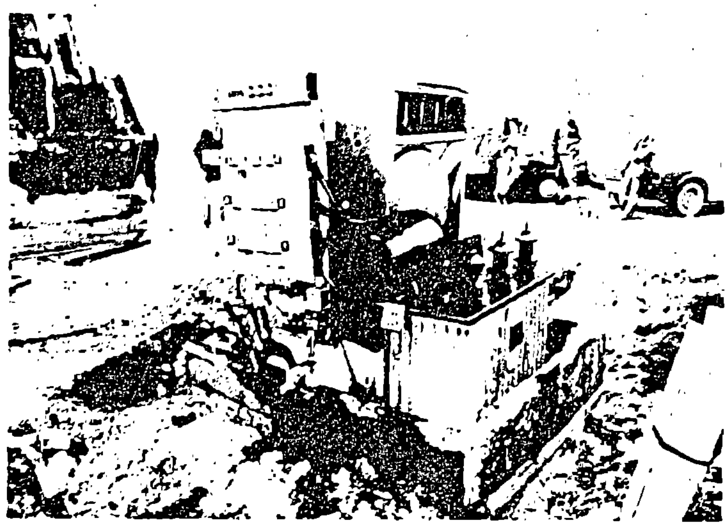


Figure B.1 The substation after the explosion.

The roof and the walls were distributed over a large area about 25 meters away from the substation. It was only the concrete foundation, the transformer, parts of the SF_6 compartment and the LV fuse arrangement which were left in the substation. As seen on Figure B.1, the SF_6 compartment and the LV fuse arrangement had also been displaced during the explosion.

B1. Dissection of the transformer

The transformer tank was insignificantly bulged, with no signs of cracks. Only a few liters of oil were lost through the breather on the conservator. By dissection of the transformer it was found that two of the four MV crossover coils in one of the outer phases (called phase A) was completely destroyed. Figure B.2 and Figure B.3 show the transformer windings.

As seen from Figure B.3, parts of crossover coils no.2 and 3 in phase A were completely melted down. Crossover coil no.1 and 4 on limb A were not damaged. Almost all the turns in coil no.2 and 3 were melted off. The melted copper was surrounded by some black and solid matter. This matter is most likely carbon and polymerization and cross-link products from hydrocarbons. By help of a scanning electron microscope and EDS (Energy Dispersive System) analysis it was concluded that the solid matter, besides carbon and hydrocarbons, also contained small copper particles and sulphur. The electrical conductivity of the solid, black matter was high. Melted copper had also burned through the outermost turn of the LV sheet winding in phase A.

Measurements of the resistance of the winding on limb A showed variation from one measurement to another. It was clear that it was poor electrical contact through the winding. The values varied from a few ohm up to about 20 MΩ.

Measurements showed that the resistance of the MV winding on limb C was as normal. The resistance of the MV winding on limb B was 8% higher. Dissection of the crossover coils on this limb showed that one turn on crossover coil no.2 was melted off. The melting of this turn had entailed that one of the tappings for the tap changer had also melted off just outside the place where the turn melted off. This did not affect the electrical circuit, because this tapping was not in use. But even if one turn had melted off, the current must still have been able to pass through the winding on limb B. It may have been electrical contact through carbonized insulation.

The measurements also showed no earth fault in the transformer, and none of the MV windings were in electrical contact with the LV windings.

B2. The cause of the transformer destruction

It is likely that the destruction of the MV coils was caused by internal short circuits between neighbouring turns or layers. Tests with short circuit between two neighbouring turns in a transformer with the same design has been described in section 7.4.1, and a picture of one of the destroyed crossover coils in this transformer is shown in Figure 7.8 on page 120.

It is almost impossible to find the reason why turns were short-circuited. One possible explanation may be that the MV insulation had been damaged or weakened earlier, for instance by lightning overvoltages or heavy overloading of the transformer. Since the transformer was destroyed only a short time after the line and the transformer had been reconnected, it is likely that the fault was triggered by the reclosing of the line and the transformer. Heavy load together with the inrush currents of the transformer may have put a too high strain on the MV conductor or the insulation.

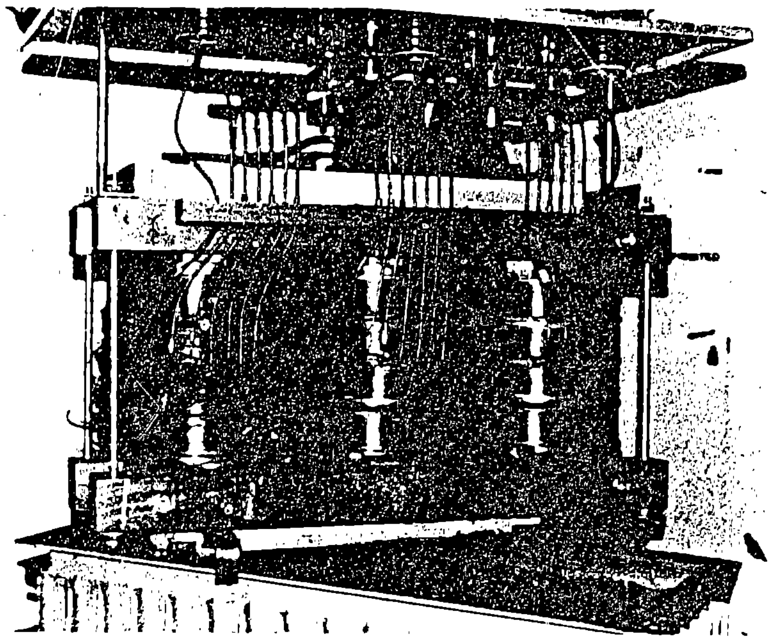


Figure B.2 The transformer windings of the transformer that was situated in the substation.

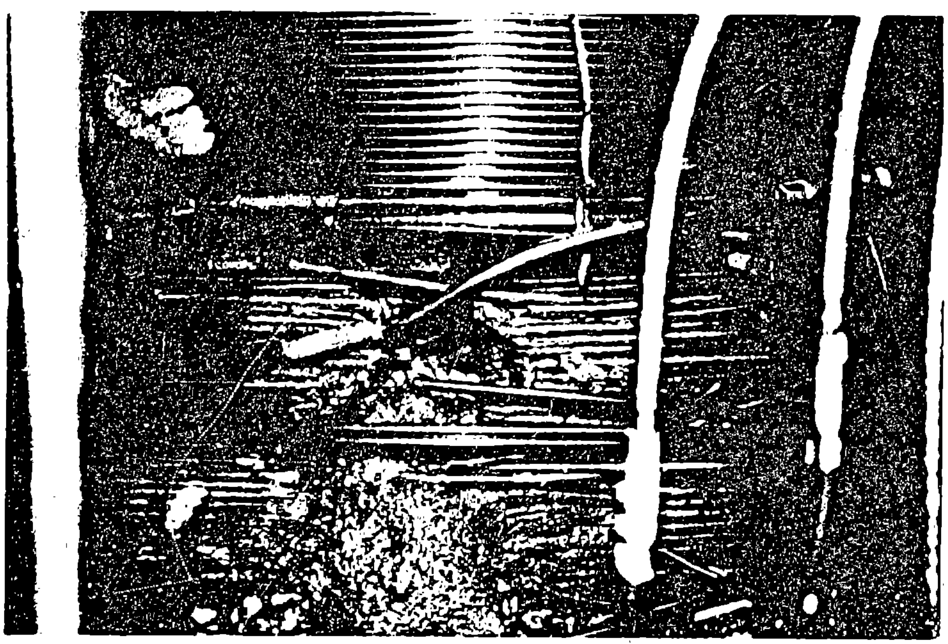


Figure B.3 Coil no.2 in phase A. This is the most destructed part of the MV winding.

B3. The reason for the explosion of the substation

As stated before the transformer had not exploded. It is evident that an internal fault in the MV winding has caused a heavy heating of parts of the MV coil. It may also have been internal arcs in the MV winding. The heavy heating, the discharges and the arcs have caused decomposition of the oil into hot gases, oil vapour or oil mist. The hot gases and the hot oil mist have flowed through the oil, the conservator and into the air in the substation. There was no ventilation in the substation. It is supposed that after some time large volumes of flammable and explosive gas mixtures and oil mist had accumulated inside the substation. A cable between the LV side of the transformer and the LV fuse panel was located close to the breather on the conservator. About 30 cm of the oversheath of extruded PVC on this cable near the breather on the conservator has been exposed to a high temperature. Parts of the oversheath is carbonized, and it is supposed that the temperature has been more than 300 °C. It is likely that hot gases and hot oil vapour flowing out from the breather on the conservator lead to the disintegration of the PVC oversheath.

In theory the explosion may have been ignited by a flash-over in the MV or LV installation. Another possible explanation is that glowing particles were transported with the evolved gases into the conservator and the substation room, thereby igniting the gas mixtures and oil vapour.

A more likely explanation is that the temperature of the gases or the oil mist flowing from the conservator have reached the self-ignition temperature. The self-ignition temperature of oil mist can be as low as 330 - 350 °C. As seen in section 6.2, different types of flammable and explosive gases are produced during different kind of thermal or electrical faults in transformer oil. From Table 6.1 on page 100 in section 6.2 it is seen that hydrogen and acetylene are produced in large amounts during electrical arcing- or sparking faults. From Table 6.3 on page 101 in section 6.2 it is seen that the explosive limits in % by volume in air are very wide for hydrogen and acetylene. The self ignition temperature of acetylene can be as low as 335 °C. It is also likely that a large amount of ethylene was produced. The explosion limit in % by volume in air for ethylene is 3.1 - 32, and the lowest self-ignition temperature is 450 °C.

B4. Melting of the MV fuse links

The MV fuses had operated in phase A and B. Dissection of these two fuses showed that they had cleared a current in the short circuit range. This was seen because the silver conductors had only melted near the constrictions.

By inspection of the MV bushings on the transformer it was found a small area ($diamter \approx 3\ mm$) with melted copper on the connection bolts in phase A and B. It is likely that an external flash-over between the bushings in phase A and B had taken place. It is likely that the short circuit current led to melting of the MV fuses. But it is not likely that the flash-over itself triggered the explosion.

B5. Conclusion

A short circuit between neighbouring turns or layers of turns in crossover coil no.2 or 3 in phase A developed further over a long time (maybe some hours). The short circuit lead to a heavy heat generation in the coils, and a subsequent decomposition of the oil into hot and flammable gases, oil vapour and oil mist. It is supposed that the explosion was a result of that the self ignition temperature was reached for one of the combustible gases or the oil mist flowing out from the breather on the conservator. The energy stored in the gases and the oil mist inside the volume of the substation may have been very high, and it seems as if the explosion has been very vigorous.

It is clear that it was very unfavorable that the transformer was protected with current limiting fuses with too high rating current. It is supposed that the line current in phase A was about $3 - 10 \times I_N$ for the transformer. From the time-current characteristics for the fuses it is seen that the melting time for the CEF-25 fuse is very long and uncertain in this overcurrent range.

It is evident that a gas relay of the Buchholz type would most likely have tripped fast for this fault.

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